Vol. 1, No. 3, p. 165-276, December 1957

An International Journal
on Fundamentals of Friction, Lubrication, Wear,
and their Control in Industry

WEAR

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AN INTERNATIONAL JOURNAL
ON FUNDAMENTALS OF FRICTION, LUBRICATION, WEAR,
AND THEIR CONTROL IN INDUSTRY

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EDITORIAL

Discussions on the 104 papers contributed to the I.M.E. London Conference are still in progress (see p. 275) while this issue is going to press. Once the Proceedings of this mammoth meeting have been published, the total of papers, discussion-remarks and authors, closures will form a unique collection of contemporary thought on a considerable number of wear problems. To serve those of our readers who have no access to the bulk of these yet unpublished papers, some of the Reviews given at the Conference will be published in a condensed form*. The contribution by DAVIES (p. 244) is the first of the series. It will thus be possible to make at least the titles of all papers, interlinked by the reviewers with current literature, gradually available. It is hoped that this procedure will facilitate future cross-reference to the 1957 London Conference.

CAMPBELL AND HARRIDEN report on the use of radioactive copper in the study of sliding friction (p. 173). Those interested primarily in the experimental apparatus will enjoy the original method of calibrating the autoradiographs with a solution prepared from an activated "blanc". It is also shown that even such a "hot" material as copper can be handled readily with a moderately modified conventional friction machine. The advantage gained by tracer studies in this field is evident from GRUNBERG AND CAMPBELL's Conference paper. Actually, it is the *combination* of a "magnification in time" by tracer technique with a "magnification in space" by e.m. microscopy which suggests the picture of that specific wear process for pure copper. The somewhat different findings for the wear of brass, studied by HIRST and his associates (p. 163), emphasize the importance of metallographic factors for the understanding of each individual wear process.

A highly specialized study of WALZEL AND ORTNER (p. 183) underlines again the significance of microstructures (German: Gefüge). The Bainitic structure, produced by isothermal phase transformation under carefully controlled conditions, has been proved to be highly resistant to wear while exposed to dry sliding in a laboratory machine. This metallographic approach is somewhat different from that of ANGUS (p. 40). In a further paper by ANGUS AND LAMB at the Conference, particular attention is given to the role played by graphite flakes as heat conductors. Taking this heterogeneous information on such a classical material as cast iron into account, it becomes increasingly clear that any attempt to formulate a "general theory of wear" would here be defeated by the flexible multiplicity of microstructures.

What might be called the *systematic* empirical approach is represented by the two contributions from the Stuttgart Group of workers (pp. 211, 225). An attempt is made to evaluate "wear data" of use to the engineer. The German Standards Committee, lead by Dr. WAHL, began at the beginning with semantic problems: the definition of con-

* The permission of the Institution of Mechanical Engineers to make use of these Review articles is gratefully acknowledged. (Ed.).

cepts. This was followed by the definition of measurable units of wear processes. In the second phase of this committee work, which is not yet completed, an attempt is made to standardize testing. The third, and final, phase of the programme forsees the evaluation not only of wear-resistant materials but also of the abrasiveness of minerals and of technical abrasives.

The Committee work is based on practical experience in industry and on the experiments of WELLINGER. Emphasis is laid here on discontinuities in the rate of wear, due to apparently minor changes in experimental conditions — a phenomenon somewhat akin to the sudden shift from *mild* to *severe* wear observed in sliding friction. This line of approach finds support from parallel studies made recently in the laboratories of Escher Wyss in Zurich (see p. 274). The problems exposed by these carefully planned tests are of such economic significance and of interest to so many industries that they deserve further study.

Dr. WAHL advocates international cooperation. It would seem that discussion of these German (provisional) standards within the framework of "*Euro-norm*", sponsored by the High Authority of the European Coal and Steel Community, Luxemburg, could be a realistic approach to this end. It will take many years, however, before such systematically standardized engineering data are available. Much can be gained in the meantime if experience in the selection of wear-resistant materials and in maintenance engineering can be shared; the papers by ALLEN (p. 232) and by DE VRIES (p. 239) illustrate this point.

Delft, November 1957 G. SALOMON
Centraal Laboratorium T.N.O.

ON KINETIC FRICTION BETWEEN UNLUBRICATED METALLIC SURFACES

F. F. LING AND EDWARD SAIBEL*

Rensselaer Polytechnic Institute, Troy, N. Y. (U.S.A.)

SUMMARY

A theory of friction between unlubricated metallic surfaces in sliding contact is proposed. For sliding conditions for which "hot" or "cold" welding of asperities is possible, the present weld-junction theory leads to a simple formulation of the coefficient of friction under idealized conditions. This result differs from that of BOWDEN AND TABOR[3] in that the coefficient of friction is found as the ratio of the shear strength to the yield pressure multiplied by a factor in which additional effects of load, relative velocity, temperature, and other physical properties appear. In arriving at this factor, the process of welding and fracturing of surface asperities is postulated to be a uni-molecular reaction.

ZUSAMMENFASSUNG

Es wird postuliert dass der Prozess des Schweissens und des Zerreissens von Oberflächenunebenheiten eine unimolekulare Reaktion ist. Dies führt zu einer Theorie der Reibung zwischen ungeschmierten metallischen Oberflächen in gleitender Kontaktreibung. Für Gleitbedingungen, wobei ,,heisses" oder ,,kaltes" Schweissen von Unebenheiten möglich ist, liefert die vorliegende Theorie der Schweissverbindungen eine einfache Formulierung des Reibungskoeffizients. Der Reibungskoeffizient ergibt sich als das Verhältnis von Schubfestigkeit zu Fliessgrenze multipliziert mit einem Faktor, in welchem der Einfluss von Belastung, relativer Geschwindigkeit, Temperatur und von anderen physikalischen Eigenschaften auftritt.

INTRODUCTION

In a previous paper "Thermal aspects of galling of dry metallic surfaces in sliding contact", the idea was developed that welding of asperities commences only after certain conditions are satisfied[1]. In that work, "welding" was taken to mean "hot" or "cold" welding and implied that the strength of the junction formed was comparable to that of "hot" welding, roughly that of the weaker parent material.

It is not our purpose in the present work to give a detailed specification of the criteria for the initiation of this type of welding, but rather, assuming that welding of junctions is taking place as one metallic body slides over the other, to analyze the situation in a semi-quantitative manner in order to arrive at the dependence of the coefficient of friction on various parameters.

To accomplish this we set up a model of the friction process as one of welding and fracturing surface asperities, and this process in turn is treated as a uni-molecular reaction following the work of LEVITSKII[2].

* Formerly of Carnegie Institute of Technology, Pittsburgh, Pennsylvania.

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In his work LEVITSKII applied the weld-junction theory to the friction process by considering the welding and breaking of *surface* molecules as a uni-molecular reaction and neglected the rate of fracturing of junctions in comparison with the rate of welding. As a result of this model and the neglect of the rate of fracturing of asperities, unrealistic results were obtained.

In the present work the concept of the uni-molecular reaction is used but a more realistic model is adopted. The energy to fracture as well as the energy to form a weld is considered. Consequently, a formulation for the coefficient of friction is arrived at which appears to have good possibilities of experimental confirmation and which may form the basis for the metallurgical and mechanical design of metals which are to slide relative to each other.

THE AVERAGE NATURE OF MEASURED QUANTITIES

Let two bodies be in sliding contact, see Fig. 1, and let F_i be the frictional resistance encountered by the i-th asperity where $i = 1, 2, \ldots, N$. It is assumed that there are on the average N asperities per unit apparent area in contact at any instant. This simplified picture deals with a time-averaged model, *i.e.*, time fluctuations do not appear. On the average, let n ($\leqslant N$) of these asperities be those which have been welded upon coming into contact; consequently $(N-n)$ of these will not have been welded. These asperities are considered to be of some average size and to be uniformly distributed. Both of these assumptions can be modified if desired to conform to any known or postulated distribution of size and arrangement.

The total frictional resistance per unit apparent area of contact, $\hat{F}$, is then

$$\hat{F} = \Sigma_{i=1}^{n} F_i + \Sigma_{i=n+1}^{N} F_i \qquad (1)$$

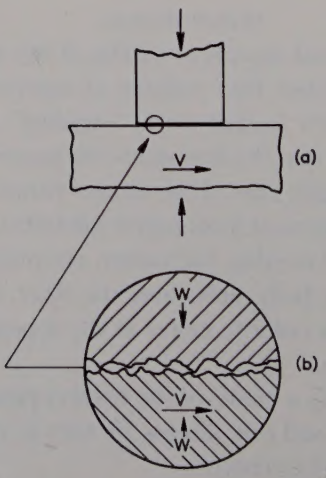

Fig. 1. (a) Two bodies in sliding contact.
(b) Enlarged view of contact surfaces showing asperities (unit apparent area of contact).

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If the normal pressure exerted on the i-th asperity of area A_i is p_i and the total applied normal load per unit apparent area of contact is W, then

$$W = \sum_{i=1}^{N} A_i p_i \tag{2}$$

The summation is carried out over all the junctions which are in contact. The ratio of eqns. (1) and (2) yields the value of the coefficient of friction f ($\equiv \hat{F}/W$), thus

$$f = \frac{\sum_{i=1}^{n} F_i}{\sum_{i=1}^{N} A_i p_i} + \frac{\sum_{i=n+1}^{N} F_i}{\sum_{i=1}^{N} A_i p_i} \tag{3}$$

The first term of the right-hand side of eqn. (3) is the weld-junction term, and the second term can be regarded as being due to a variety of causes. For the sake of simplicity it will be referred to as the "non-welding" effect. This paper is primarily concerned with the study of the weld-junction term. Let this term be denoted by f_w. Under ideal conditions in which the shear strength of junctions and the normal pressure are constant, having values s and p respectively, the first term of the right-hand side of eqn. (3) becomes

$$f_w = \frac{s \sum_{i=1}^{n} A_i}{p \sum_{i=1}^{N} A_i} \quad (n \leqslant N) \tag{4}$$

Moreover, if the A_i's are approximately equal and each is designated by "A", then approximately

$$f_w = (n/N)\,(s/p) \tag{5}$$

Equation (5) gives a form for f_w from the weld-junction point of view but differs by a factor n/N from that of BOWDEN AND TABOR[3]. The following section is devoted to establishing this factor.

WELDING AND FRACTURING OF ASPERITIES

Suppose one body slides relative to another at constant speed and conditions are such that surface asperities are welded and then fractured. Let $\mathrm{d}x/\mathrm{d}t$ be the rate at which welded junctions per unit apparent area of contact are formed, and let $\mathrm{d}y/\mathrm{d}t$ be the rate at which they are fractured. Considering this process in the first approximation to be a uni-molecular reaction,

$$\mathrm{d}x/\mathrm{d}t = K_w\, y - K_f\, x \tag{6}$$

which is to say that the rate at which asperities are welded increases as the number which have been fractured increases, and decreases as the number which have been welded increases. Here it is assumed that the same conditions prevail at each instant, that is, neither body changes as regards the number, size or distribution of asperities,

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thus

$$x + y = N \tag{7}$$

or

$$\mathrm{d}x/\mathrm{d}t = -\,\mathrm{d}y/\mathrm{d}t \tag{8}$$

where N is the number of surface asperities per apparent area of contact. Equations (6) and (7) yield.

$$\mathrm{d}x/\mathrm{d}t = K_w\,(N - x) - K_f\,x \tag{9}$$

and integrating these results for the number of welded asperities per unit apparent area of contact

$$x(t) = N\,\frac{K_w}{K_w + K_f}\,[1 - \mathrm{e}^{-(K_w + K_f)t}] \tag{10}$$

where we have assumed that for $t = 0$, $x = 0$.

Equation (10) represents the number of junctions formed as a function of time. Now, if L is the average distance between asperities and v is the relative velocity of sliding, then the time elapsed before the above process repeats itself in this average model would be L/v. Differentiating eqn. (10) we get the rate at which junctions are formed at any time, $\mathrm{d}x/\mathrm{d}t$. Let the total number of welds formed during each repeating interval from $t = 0$ to $t = t_e$ be n; this may be expressed

$$n = \int_0^{t_e} (\mathrm{d}x/\mathrm{d}t)\,\mathrm{d}t = \int_{x(0)}^{x(t_e)} \mathrm{d}x = x(t_e) - x(0)$$

where t_e is L/v. Since $x(0) = 0$, there results $n = x(t_e) = x\,(L/v)$. From equation (10) and the above consideration we have

$$n/N = \frac{K_w}{K_w + K_f}\,[1 - \mathrm{e}^{-(K_w + K_f)L/v}] \tag{11}$$

Referring to eqn. (5), n/N is the multiplying factor to the s/p ratio which is the formulation for the weld-junction part of the coefficient of friction according to BOWDEN AND TABOR.

From reaction-rate theory the rate coefficients K_w and K_f can be expressed in the form

$$\begin{aligned} K_w &= C_w\,\mathrm{e}^{-E_w/RT} \\ K_f &= C_f\,\mathrm{e}^{-E_f/RT} \end{aligned} \tag{12}$$

where T is the absolute temperature, R is the universal gas constant, and E_w and E_f are the energies to weld and to fracture respectively. The quantities C_w and C_f are practically independent of temperature, and in the first analysis let us assume $C_w = C_f = C$ and eqns. (5), (11) and (12) yield

$$f_w = (s/p)\,\frac{1}{1 + \mathrm{e}^{(E_w - E_f)/RT}}\left\{1 - \exp.\left[-\frac{LC}{v}\,(\mathrm{e}^{-E_w/RT} + \mathrm{e}^{-E_f/RT})\right]\right\} \tag{13}$$

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This equation shows the dependence of f_w on temperature and velocity. The temperature T is the temperature at the junction areas and results from bulk temperatures of the bodies and temperature rises due to frictional heating, the latter being dependent on the relative velocity, load, and thermal properties of the materials. The activation energies will depend on surface conditions such as existence of surface films and their depths and strengths. Only the average distance between asperities enters in the above, but in a more detailed analysis the statistics of asperity size and distribution will have to be considered.

QUALITATIVE CONCLUSIONS

If we neglect the interaction of velocity and temperature, an assumption not too serious for small velocity, it may be seen that the following qualitative conclusions may be drawn:

(1) as v increases, f_w decreases (f_w may increase in cases where an increase in v causes a sizable increase in T)

(2) for constant v,

(a) if $E_w \geqslant E_f$, an increase in T causes an increase in f_w.

(b) if $E_w < E_f$, an increase in T causes a decrease in f_w.

(c) if v is small, the factor multiplying the ratio s/p is approximately 1/2 when $E_w \approx E_f$.

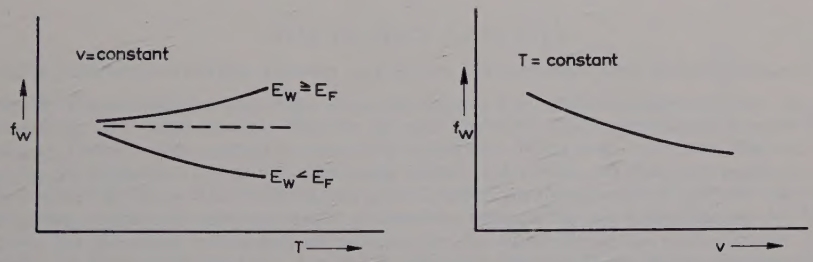

Fig. 2. Qualitative sketch showing relationships of f_w to temperature and velocity.

These results are depicted schematically in Fig. 2 and follow at least qualitatively known experimental results (see for example ref.[4,5,6] for effect of velocity on f_w and ref.[7] for effect of temperature on f_w).

At the present time, no attempt is made to draw quantitative conclusions since pertinent data are very meager. However, it is felt that the model which has been assumed represents a definite advance over previous work, in that temperature and velocity dependence of f_w appear explicitly and in a form that may suggest an approach to the design of new experiments.

This work may be extended to include the second term on the right-hand side of eqn. (3), the "non-welding" effect. However, it is the object of this work to discuss only cases where this effect is of secondary importance.

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ACKNOWLEDGEMENT

This work was supported in part by the Office of Ordnance Research, U. S. Army.

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Received September 2, 1957

USE OF RADIOACTIVE SPECIMENS ON A KINETIC BOUNDARY FRICTION MACHINE

R. B. CAMPBELL AND G. HARRIDEN

Mechanical Engineering Research Laboratory, Thorntonhall, Glasgow (Scotland)

SUMMARY

Modifications to a kinetic boundary friction machine necessitated by the use of radioactive copper as the smaller rubbing contact are described. The radioactive specimen was fitted with the aid of specially designed jigs. Lead shielding reduced the counting rates recorded at various positions round the machine to acceptable levels. Photographic methods were used to detect copper which had been transferred to the mating steel surface. A method for making quantitative assessment of an autoradiograph is described as is a time-saving graphical method of handling the experimental results. The machine was found to be well suited for use in conjunction with radioactive techniques and examples of the type of result which can be conveniently obtained by these techniques are given.

ZUSAMMENFASSUNG

BENUTZUNG VON RADIO-AKTIVEN PROBEN AUF EINER KINETISCHEN GRENZSCHMIERUNGS-MASCHINE

Es werden Konstruktionsänderungen einer kinetischen Grenzschmierungsmaschine beschrieben, die Benutzung von radio-aktivem Kupfer als den kleineren Reibungskontakt ermöglichten. Die radio-aktive Probe wurde mittels besonders angefertigter Werkzeuge montiert. Bleiabschirmung verringerte die Zählraten, die an verschiedenen Stellen in der Nähe der Maschine gemessen wurden, auf annehmbare Niveaus. Eine Methode wird beschrieben zur quantitativen Auswertung von Autoradiographien, sowie eine zeitersparende, graphische Technik für die Ausarbeitung der Versuchsergebnisse. Die Maschine erwies sich als geeignet für die Anwendung von radio-aktiven Versuchsmethoden. An Beispielen wird die Art der Ergebnisse, die mit Hilfe dieser Versuchsmethoden erhalten werden können, gezeigt.

INTRODUCTION

The amount of metal transfer which takes place during a single sliding process can be very small, so that extremely sensitive methods must often be used for its detection. The development of radioactive techniques has produced a very sensitive and convenient method of detecting transfer between rubbing surfaces. Not only can small quantities of metal be measured, but it is also possible to ascertain the distribution of the transferred material. Transfer between specimens of the same material can be studied, an added advantage over chemical or electrographic methods, which in any case lack the sensitivity of radioactive techniques.

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The development of these radioactive techniques is particularly valuable since it is now generally accepted that measurement of the friction developed between surfaces in rubbing contact gives, by itself, a very incomplete picture of the processes occurring in the contact zone. The picture can best be supplemented by studying surface damage and metal transfer.

A number of workers have used radioactive methods to measure transfer in friction experiments. Amongst the earliest papers dealing with the application of radioactivity in this field are those of SAKMANN *et al.*[1] in 1944 and GREGORY[2] in 1946. Although the method has been used fairly frequently since then (*e.g.* by RABINOWICZ[3] and by HIRST, KERRIDGE AND LANCASTER[4]) it has its limitations, and to obtain the greatest possible sensitivity radioactive material in a high state of activation must often be used. Always an important consideration is the amount of activity that must be handled. In the more usual form of kinetic boundary friction machine the weight of the smaller of the two rubbing specimens is about 1 gram. When such a specimen is activated by irradiation in an atomic pile the resultant activity must often be of the order of 100 mc if transfer in the region of 10^{-10} g is to be measured. Since only the surface layer is involved in wear, plating from a bath of radioactive solution could be used to reduce the activity which must be handled during a friction experiment. In practice, however, plating methods tend to have a number of disadvantages. For example the plated specimens have to be polished whilst active, whereas the rubbing surface of a specimen irradiated in bulk can be prepared before irradiation. The present paper describes how sources of up to a few hundred millicuries of radioactive copper can be handled on a kinetic boundary friction machine. A convenient graphical method for making quantitative use of the experimental results is also described.

APPARATUS

The kinetic boundary friction machine used for the radioactive experiments consisted of a small hemispherical upper contact loaded against a flat lower specimen which was moved at relatively slow speed. In detail the machine was similar to that used by BRISTOW[5] and by BARWELL AND MILNE[6]. The lower flat specimen is mounted on a trolley which can be driven at constant velocity by a hydraulic ram. Since it is usual for repeated runs to be made on the same specimen, the specimen sits in a traversing mechanism consisting of a spring-loaded gate. This permits shifting of the lower specimen sideways, at right angles to the direction of motion of the trolley, prior to a subsequent run. A fresh surface is thus provided for each new track to be made.

The upper contact is by far the smaller of the two rubbing specimens and is the obvious one to make radioactive. It consists of a small hemispherically ended stud as shown in Fig. 1, and when made of copper, as in the present experiments, weighs almost exactly 1 gram. The hemispherical end is the point of contact between the two specimens. To facilitate repeated runs using the same upper specimen, the specimen, in a specimen holder, is mounted obliquely on a bridge which is at right angles to the direction of motion of the trolley. The upper specimen can be rotated between

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Fig. 1. The upper specimen with tail.

experiments so as to give different points of contact for each new track. Varying loads can be applied directly to the cross bridge on which the upper specimen is mounted by means of a lever arrangement. A mechanism fitted to the cross bridge enables the test surfaces to be contacted or separated and the load to be applied or relieved between runs. With the specimens in contact and a load applied, the upper specimen is restrained from moving freely in the direction of motion of the lower specimen by connecting the cross bridge to an unbonded resistance strain gauge. During the course of a test the output from the strain gauge was fed into a pen recorder of the continuous chart type. Calibration was achieved by direct application of known forces to the strain gauge. A continuous record of the friction developed in the contact zone could thus be obtained.

This type of kinetic boundary friction machine was found to lend itself very readily to use in conjunction with radioactive materials. The upper specimens from the viewpoint of size can easily be activated in an atomic pile.

PROCEDURE

The object of the experiments in which radioactive copper was used as the upper specimen was to investigate the effect of sliding velocity and of surface roughness on friction and metal transfer under conditions of boundary lubrication. Mild steel, finish-

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ed to varying degrees of surface roughness, was chosen as the lower flat specimen. Two lubricants at the extreme levels of boundary lubrication effectiveness, liquid paraffin and oleic acid, were used. The upper specimens were machined from high conductivity copper, and the hemispherical ends were ultimately polished to a good finish with alumina powder. After degreasing, the copper specimens were sent to Harwell to be activated to saturation activity in the atomic pile. The short half-life of the radioactive copper necessitated using the specimens as soon as possible after receipt from Harwell. When an experiment was to be carried out with a radioactive specimen the specimen was gripped in long-handled tongs and dropped down the funnel of the brass container illustrated in Fig. 2. The container was then inserted in the loading jig illustrated in Fig. 3 and the locating funnel part of the container was removed. The specially

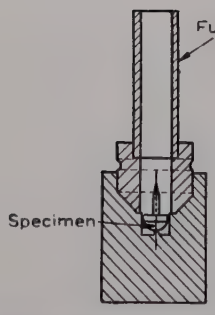

Fig. 2. Specimen container with locating funnel.

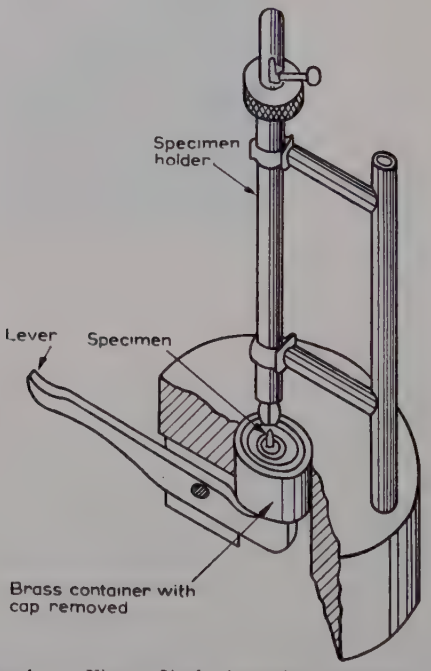

Fig. 3. Jig for inserting specimen into holder.

designed combined specimen-holder and handling tool shown in Fig. 4 could then be swung into position above the tapered tail of the specimen. By depressing a lever the specimen in its container was lifted to the open jaws of the chuck type holder, which were then closed around its tail. Release of the lever allowed the container to fall away from the specimen. The upper specimen holder with the test piece was then transferred to a swinging guide arm on the friction machine and swung into position on the machine. The guide arm can be seen in Fig. 5. Positive location of the specimen on the machine was obtained by screwing the handling tool into a brass block mounted on

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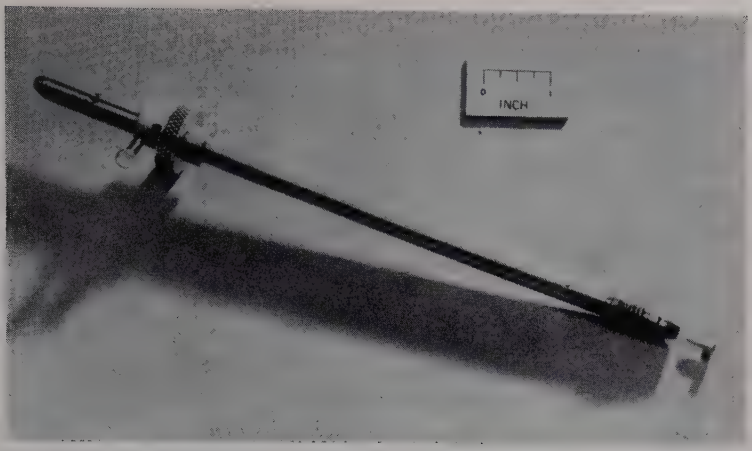

Fig. 4. Combined specimen holder and handling tool.

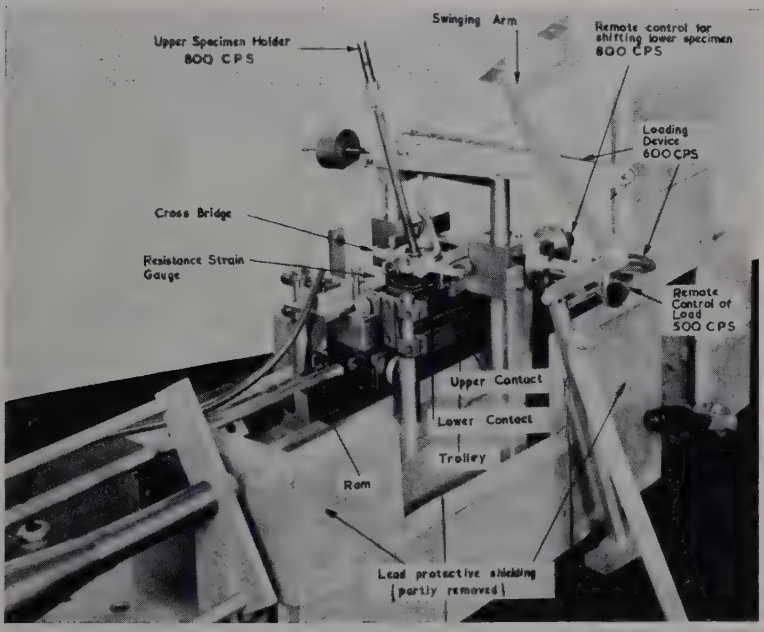

Fig. 5. The kinetic boundary friction machine with part of the lead shielding removed. The "CPS" values give the counting rates in counts per second at the positions indicated when a radioactive specimen is in position.

the cross bridge, a double start thread giving quick tightening action onto the taper of the chuck jaws. The devices described allowed the operation of fitting the radioactive specimen to be carried out in about five seconds.

As mentioned in the previous paragraph, activation in the atomic pile was carried through to saturation and the activity immediately after removal from the pile was about 600 mc. The short half-life often necessitated immediate use of the active ma-

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terial and experiments were frequently carried out one day after removal from the pile. Since the half-life of radioactive copper is 12.8 hours, the activity to be handled during a friction experiment was often of the order of 100 mc, mainly β activity but with some λ activity. Consequently the area of the machine in which the radioactive upper specimen was situated was shielded with lead bricks as shown in Fig. 5. Quite high levels of activity could then be handled without undue exposure of personnel. With the monitoring equipment available the maximum permissible exposure of 0.5 mr/40 h was equivalent to about 120 counts/sec. With a "day old" radioactive specimen in position the machine was monitored. Fig. 5 shows the counting rates recorded at various positions round the machine at which exposure seemed likely. Although these exceed the permissible rate, exposure in these positions was always brief.

When both specimens were in position and in rubbing contact, the trolley was set in motion at a pre-set constant velocity and the experiments were conducted in accordance with the usual test procedure. The mechanism for contacting or separating the test surfaces between runs could be operated from behind the lead shielding. The traversing mechanism permitting lateral shift of the lower specimen could easily be operated by depression of a knob at the end of the trolley without undue exposure to the radioactive button. The long holder carrying the radioactive specimen could be rotated and locked from the "inactive" end so as to give twelve different points of rubbing contact.

EVALUATION OF RESULTS

After a sliding experiment the lower specimen carrying the friction tracks was exposed to X-ray film. The radioactive material transferred from the upper specimen produced blackening of the film on subsequent development, *i.e.* an autoradiograph formed. This photographic method of detecting the transfer is particularly suitable when a soft hemispherical specimen is slid on a harder flat specimen, as in the present experiments. The amount and distribution of the wear particles adhering to the flat surface could be determined with a fair degree of accuracy from the blackening they produced, since the absence of a track groove on the flat surface led to increased definition in the autoradiographs. An incidental advantage of using a softer material for the upper contact than for the lower specimen was that it avoided large scale pick-up of metal from the latter. When heavy transfer occurred fine-grained films such as Kodak Crystallex or Ilford Industrial C provided excellent autoradiographs of good definition after a few hours exposure. When transfer was light a faster film such as Ilford Industrial G was used. The films were developed according to a standard procedure to facilitate comparison of the results obtained from different experiments.

The photographic method of detecting activity, and hence of detecting transfer, has advantages over direct counting methods in convenience and in the range and variety of information obtained. In favourable cases down to 10^{-12} g of active material can be detected, and a permanent record of the detailed distribution of transferred material is automatically produced. Even if no attempt is made to obtain quantitative

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estimates of transfer from the films the autoradiographs of the tracks on any one lower specimen are directly comparable, since they receive the same exposure and development. In the case of the present experiments the effect of sliding velocity on transfer under conditions of boundary lubrication is well illustrated by the autoradiograph shown in Fig. 6. The short tracks correspond to a sliding velocity of 0.001 cm/sec and the three long tracks furthest from the shortest tracks correspond to a sliding velocity of 0.3 cm/sec. The tracks in between these two groups correspond to intermediate sliding velocities. The decrease in optical density, and hence in transfer, which occurs with increase of sliding velocity can be clearly seen. A comparison of autoradiographs derived from different lower specimens showed the effect to be most marked when the surface of the lower specimen was roughly finished. This is typical of the type of information which can be obtained without detailed measurement of the autoradiographs.

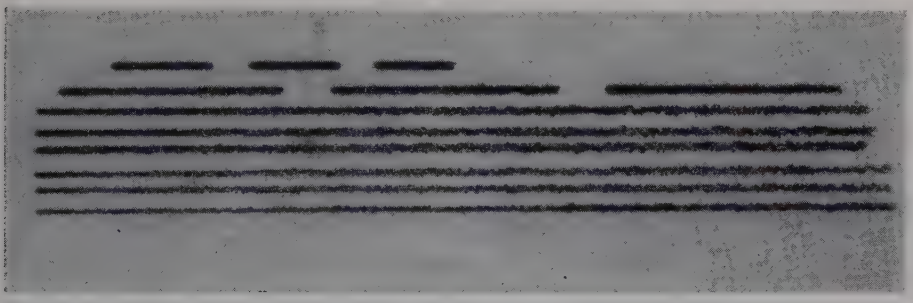

Fig. 6. Autoradiograph from friction tracks.

QUANTITATIVE ASSESSMENT OF AN AUTORADIOGRAPH

Counting methods are superior to autoradiographic techniques where high quantitative accuracy in detecting radioactive material is required. However, a method using autoradiographic techniques, whereby an accurate quantitative estimate of transfer was obtained, will now be described.

A small copper cylinder cut from the same piece of metal as the copper stud to be used in a friction experiment and weighing about 0.1 g was activated in the pile at the same time as the test specimen. When the active material was received from Harwell the small cylinder was dissolved in nitric acid and various dilutions of the solution thus obtained were prepared. Drops containing known amounts of radioactive copper were then deposited on a steel "calibration" specimen, which was similar in surface finish to that to be used in the friction experiment. On drying, a series of spots containing varying amounts of copper was produced. This calibration specimen was then exposed for the same time and to the same sheet of X-ray film as the lower specimen from the friction experiment. This procedure provided autoradiographs of the tracks from the friction experiment and of the calibration spots, on which accurate measurements of optical density were made. The amount of copper deposited in the friction tracks could then be determined by interpolation from the figures for blackening produced by the calibration spots.

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Optical density measurements were carried out using a Hilger microphotometer. The slit width of the photometer was adjusted to be slightly less than the narrowest part of the track to be measured and the length of the slit was adjusted to be 0.5 mm. If D is the optical density, B the reading corresponding to the density of the background, and G the reading corresponding to density D, then

$$D \propto (\log B - \log G) \tag{1}$$

The optical densities must now be converted to amount of copper transferred, T. The response of photographic materials to $\beta - \gamma$ radiation can be expressed over a considerable range by

$$D \propto \log_8 E \tag{2}$$

where E is the product of intensity and time. Now $E \propto T$ hence

$$T \propto (\log B - \log G) \tag{3}$$

Data drawn from the calibration autoradiographs permit solutions of equation (3) to be obtained for any desired points on the autoradiograph of a friction track. If measurements are carried out at 0.5 mm intervals along a friction track, then photometry of a single track can involve taking up to 150 readings. The numerical evaluation of equation (3) for each point on the track is very time-consuming, and a graphical method was employed. Using data from a calibration autoradiograph the known figures for deposited metal were plotted against the corresponding photometer reading on double-log. paper. This produced a curve of shape shown in Fig. 7. The figure for transfer at any point on the corresponding test film could be read from the graph after a photometer reading had been taken at the appropriate point on the test film.

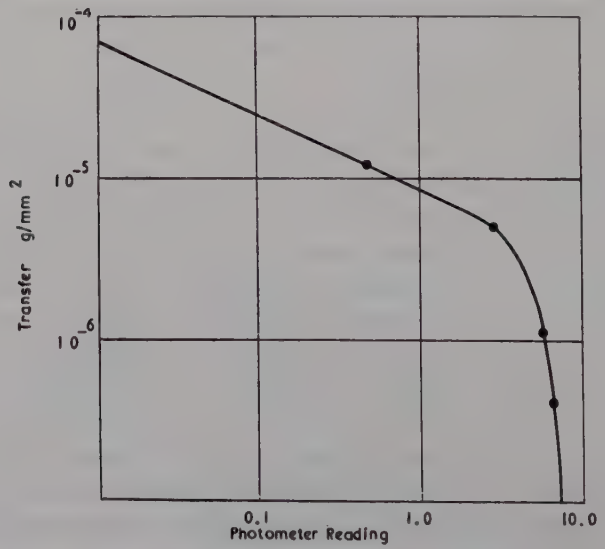

Fig. 7. Calibration curve consisting of transfer plotted against photometer reading.

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Application of a slight variation of this procedure for quantitative evaluation of the autoradiographs permitted a detailed examination of the role of metal-to-metal contact in the sliding process. Curves were plotted of the photometer readings at 0.5 mm intervals along the friction tracks against distance from the origin. Semi-log paper was used for the graph, and the photometer readings were plotted on the inverted log. axis. By reference to a calibration curve such as is shown in Fig. 7, the "photometer reading" scale was replaced by a scale giving metal transfer in terms of g copper/mm². For every friction track the curves of coefficient of friction against distance and of metal transfer against distance were then combined with a suitable enlargement of the appropriate autoradiograph. Fig. 8 shows an example of such a record. Ultimately, a new model for the nature of the metal-to-metal interactions taking place in the contact zone was postulated as a direct consequence of the accurate quantitative data obtained from the autoradiographs.

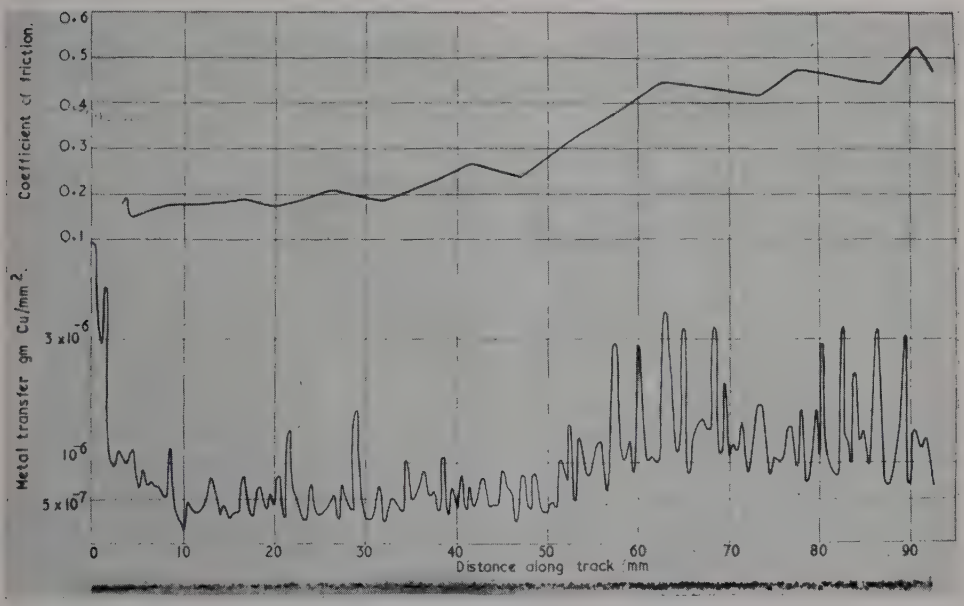

Fig. 8. Combination of curves for coefficient of friction and for metal transfer with the appropriate autoradiograph.

CONCLUSION

The type of kinetic boundary friction machine in which a small hemispherical contact is loaded against a flat specimen is well suited for use in conjunction with radioactive methods of detecting transfer. Great sensitivity is possible, and if autoradiographic techniques are used a permanent record of the distribution of transferred material is easily obtained. Graphical methods can be used advantageously in proceeding to an estimate of transfer from measurements of optical density on the autoradiographs.

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The benefits which ensue from the use of radioactive methods are well illustrated in a recent investigation by GRUNBERG AND CAMPBELL[7]. The effects of surface roughness and sliding velocity in the boundary lubrication process were clearly established. Rough surfaces caused considerable metal transfer, which could not be completely avoided even by use of a "good" boundary lubricant. When metallic friction formed a significant proportion of the total friction as evidenced by the appreciable transfer, friction decreased with increase of sliding velocity. The work hardening properties of the copper upper specimens manifested themselves in periodic fluctuations in friction and transfer. This phenomenon was brought out clearly by the combination of friction record with the autoradiograph of the appropriate friction track. The combination permitted detailed comparison of the instantaneous values of friction and transfer.

ACKNOWLEDGEMENTS

The work described was carried out in the Lubrication and Wear Division of the Mechanical Engineering Research Laboratory and is published by permission of the Director of Mechanical Engineering Research, Department of Scientific and Industrial Research.

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Received August 14, 1957

BEITRAG ZUR KENNTNIS DES VERSCHLEISSWIDERSTANDES VON GUSSEISEN MIT ZWISCHENSTUFENGEFÜGE

RICHARD G. WALZEL UND HERMANN ORTNER*

Eisenhütteninstitut der Montanistischen Hochschule, Leoben (Österreich)

ZUSAMMENFASSUNG

Es wurden zwei Gußeisensorten mit Lamellengraphit auf ihr Gefüge und auf ihre Eigenschaften nach isothermen Umwandlungen im Zwischenstufenbereich untersucht und mit den gleichen Gußeisen nach gewöhnlicher Vergütung (martensitisches Abschrecken und Anlassen) auf gleiche Brinellhärte verglichen. In den Vergleich wurden weiters der Gußzustand und der martensitische, nicht angelassene Zustand einbezogen. Hiebei wurde erkannt, daß eine isotherme Umwandlung im Bereich der unteren Zwischenstufe bei 350°C ein günstiges Verhältnis der Zähigkeit zur Härte bringt. Insbesondere aber bei vergleichenden Verschleißversuchen auf einer Verschleißprüfmaschine besonderer Bauart, die die Kaltverformung der Oberflächenzone als eine Komponente des Verschleißvorganges mitberücksichtigt, wurde eine starke Übergelegenheit des Verschleißwiderstandes des Zwischenstufengefüges gegenüber dem gewöhnlichen Vergütungsgefüge festgestellt. Dies bestätigt grundsätzlich die Schrifttumsangaben und gibt auch einen weiteren Hinweis, daß der Rest-austenit im Zwischenstufengefüge und dessen nachträgliche Umwandlung in Martensit infolge der Kaltverformung während des Verschleißvorganges, sowie die verhältnismäßig hohe Zähigkeit für diese Überlegenheit des Zwischenstufengefüges verantwortlich sind. Es tritt diese aber offenbar nur in einem verhältnismäßig engen Bereich der Zwischenstufenvergütung auf.

SUMMARY

A CONTRIBUTION TO THE KNOWLEDGE OF WEAR-RESISTANCE OF BAINITIC-HARDENED CAST IRON

The structure and properties of two grades of cast iron with flake graphite have been investigated after isothermal transformation in the "tempering" range of bainitic hardening. They were compared as regards structure and properties with the same grades of cast iron after a normal hardening and tempering, *i.e.* oil quenching resulting in a martensitic structure, followed by tempering until the same Brinell hardness is reached as with the bainitic hardening. Comparison was also made with the martensitic, untempered condition. It was found that isothermal transformation, but only in the lower bainitic hardening range (350°C), gives a favourable ratio between toughness and hardness. Particularly when comparing the wear-resistance, the superiority of this bainitic-hardened cast iron over the normally hardened and tempered cast iron was established. These comparative experiments were carried out with a specially constructed wear-testing machine, designed to take into account the influence of the cold-working of the surface zone as an important component of the wear process. Our data confirm in principle the results reported in the literature and emphasize once more the importance of residual austenite present in the Bainite and its subsequent transformation into martensite by cold-working during the wear process. This structure, together with the comparatively high value of toughness of this grade of cast iron, is responsible for the superior wear-resistance of bainitic iron. However, this superiority becomes apparent only over a comparatively small range of the bainitic hardening process.

Über die isotherme Umwandlung zur Erzielung eines Zwischenstufengefüges (Bainit) an Gußeisen und über die Eigenschaften, die mit einem solchen Gefüge erreicht werden, liegen bereits mehrfache Untersuchungen vor. Es genügt hier, auf zusammenfassende

* Zur Zeit Pretoria.

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Abhandlungen zu verweisen, wie VON HUMMEL UND PIWOWARSKY[1] und GUHL[2], die eingehende Schrifttumshinweise bringen.

Das hier besonders interessierende Problem des *Verschleißwiderstandes* von Gußeisen mit Zwischenstufengefüge wurde erstmalig von BARTHOLOMEW[3] behandelt. Er hat erkannt, daß durch Zwischenstufenvergütung der Verschleißwiderstand des Gußeisens überraschend hoch gesteigert werden kann; die Laufzeit (Lebensdauer) von Kammwalzen aus Gußeisen, die er auf Zwischenstufengefüge vergütet hatte, betrug etwa das 6-fache von jenen, die durch gewöhnliche Vergütung (Ölabschreckung auf Martensit und Anlassen) *auf die gleiche Brinellhärte* von 360 kg/mm² gebracht worden waren. Weniger überraschend ist die weitere Feststellung, daß die genannten, auf Zwischenstufengefüge vergüteten Kammwalzen eine etwa 200-fach längere Laufzeit aufwiesen als die Kammwalzen im unvergüteten Gußzustand mit einer Brinellhärte von nur 228 kg/mm², da es ja grundsätzlich bekannt ist, daß unter sonst gleichen Voraussetzungen der Verschleißwiderstand mit der Brinellhärte stark ansteigt. Die Notwendigkeit, bei Vergleichen der Verschleißwiderstände von der Basis gleicher Brinellhärte auszugehen, wurde von späteren Autoren, z.B. OHLY[4] nicht immer berücksichtigt. Wohl aber scheinen dies zwei neuere Untersuchungen zu tun, die hier allerdings nur nach dem zusammenfassenden Bericht von GUHL[2] wiedergegeben werden können: KURTOV UND SADIN[5] fanden bei Vergleichsversuchen auf der bekannten Verschleißprüfmaschine nach M. SPINDEL einen (zwar nur um 25-50%) höheren Verschleißwiderstand des zwischenstufenvergüteten gegenüber gewöhnlich vergütetem Gußeisen; KANTOR, KULIKOW UND IWANJUSCHIN (nach H. TAUSCHER[6]) hingegen stellten eine 27-fache Überlegenheit des ersteren fest, wobei allerdings die Prüfbedingungen nicht bekannt sind.

Nach allem wird man eine Überlegenheit des Verschleißwiderstandes von Gußeisen, das durch isotherme Umwandlung auf Zwischenstufengefüge gebracht worden ist, gegenüber dem gleichen Gußeisen, wenn es durch gewöhnliche Vergütung die gleiche Brinellhärte erreicht hat, grundsätzlich erwarten dürfen. Nach DEMIDOWA UND KUNJAWSKI[7], zitiert nach GUHL[2], liegt die Ursache in einem geringen (oder manchmal auch größeren) Gehalt an Rest-austenit, der bei der Zwischenstufenvergütung zurückbleibt und sich nachträglich durch die Kaltverformung, die mit der Verschleißbeanspruchung Hand in Hand geht, in Martensit mit hohem Verschleißwiderstand verwandelt.

Wenn auch diese Untersuchung an Gußeisen mit Kugelgraphit durchgeführt worden war, so dürfte sie doch eine auch auf andere Gußeisensorten übertragbare einleuchtende Erklärung für die Überlegenheit der Zwischenstufenvergütung bieten, so lange diese einen Rest von Austenit zurückläßt; es ist hiebei auch vorstellbar, daß ein solcher Rest gar nicht immer im Mikroskop erkennbar zu sein braucht, d. h. er kann unter Umständen auch in scheinbar vollständig isotherm umgewandeltem Gußeisen noch vorhanden sein. Daraus folgt aber auch, daß es offenbar wesentlich auf die Art der Zwischenstufenvergütung und die Art des erreichten Zwischenstufengefüges ankommt, welches Ausmaß die Überlegenheit gegenüber einem gewöhnlichen Vergütungsgefüge mit gleicher Brinellhärte annimmt. Weiters ist zu beachten, daß erfahrungsgemäß die Ergebnisse von vergleichenden Verschleißversuchen sehr stark von der

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verwendeten Verschleißprüfmaschine abhängen; gerade wenn man sich die Vorstellung zu eigen macht, daß im Zwischenstufengefüge eine nachträgliche Umwandlung des Rest-austenits in Martensit durch Kaltverformung während der Verschleißbeanspruchung den hohen Verschleißwiderstand bringt, kommt es offenbar darauf an, ob die verwendete Verschleißprüfmaschine im wesentlichen nur eine Abscheuerung bewirkt oder ob der Abtrennung der Teilchen von der Oberfläche deren starke Kaltverformung (Quetschung) vorausgeht. Zu diesen Fragen, die unter Umständen entscheidend wichtig sind, sei auf die Abhandlung von WALZEL[8] verwiesen.

An Hand solcher Überlegungen lassen sich die im Schrifttum erscheinenden starken Abweichungen des Ausmaßes der Überlegenheit von zwischenstufenvergütetem Gußeisen erklären. Es dürfte aber auch erwünscht sein, die bisherigen, immerhin noch schmalen Unterlagen zu dieser Frage durch weitere vergleichende Verschleißversuche unter möglichst genau definierten Bedingungen zu ergänzen.

In dieser Absicht ist die vorliegende Arbeit entstanden. Sie setzt sich zum Ziel, auf einer Verschleißprüfmaschine besonderer Bauart, durch die eine stärkere Hervorhebung der Kaltverformungskomponente in der Verschleißbeanspruchung als bei der Maschine nach M. Spindel erzielt wird, Gußeisen einerseits nach isothermer Umwandlung auf Zwischenstufe und anderseits nach gewöhnlicher Vergütung (martensitisches Abschrecken in Öl und Anlassen) zu vergleichen. Daß hiebei auf strenge Einhaltung der gleichen Brinellhärte in beiden Fällen geachtet wurde, braucht nach dem früher Gesagten nicht besonders betont zu werden. Lediglich zur Vervollständigung des Bildes wurde auch der martensitische, nicht angelassene Zustand (mit naturgemäß wesentlich höherer Brinellhärte) und der unbehandelte Gußzustand (mit wesentlich niedrigerer Brinellhärte) in den Vergleich einbezogen. Zugrunde lagen Gußeisensorten mit Lamellengraphit, der ja durch keine der Behandlungen beeinflußt wird.

Den Verschleißversuchen wurden Gefügeuntersuchungen, im besonderen auch im Zusammenhang mit dem Fortschreiten der isothermen Umwandlung, sowie Festigkeits- und Zähigkeitsuntersuchungen vorangestellt.

Verwendet wurden zwei im Kupolofen hergestellte Gußeisenschmelzen mit folgenden Zusammensetzungen:

Gußeisen:	C	Si	Mn	P	S	Cr	Mo %
A	3.26	2.46	0.55	0.76	0.125	—	—
B	3.43	1.60	0.43	0.57	0.105	0.23	0.25

Es wurden Stäbe mit 35 × 25 mm Querschnitt und etwa 400 mm Länge in Sand gegossen. Daraus wurden Stäbe mit 12 mm Durchmesser und 40, bzw. 120 mm Länge für die vorbereitenden Umwandlungs- und die Biegeversuche gedreht und Stäbe mit den Abmessungen 30 × 20 × 60 mm für die Verschleißversuche gehobelt. Dann folgte die Wärmebehandlung und bei den Verschleißproben einseitig das Schleifen auf Schmirgelkörnung 00.

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(True magn. × 600; reduced in repr. 0.8)

Abb. 1. Gußeisen „A" Gußzustand.

(True magn. × 600; reduced in repr. 0.8)

Abb. 2. Gußeisen „B" Gußzustand.

Das Gefüge im Gußzustand zeigt Abb. 1 für das Gußeisen A und Abb. 2 für das Gußeisen B. Die Brinell- und Rockwell C-Härten sind unter den Bildern angegeben.

Durch Vorversuche war festgestellt worden, daß für die vollständige Austenitisierung ein Halten von 15 Minuten bei 900°C für Gußeisen A und bei 860°C für Gußeisen B richtig ist. Weiters konnte die Zeitabhängigkeit der isothermen Umwandlung nach dem Abschrecken von dieser Austenitisierungstemperatur im Salzbad von 450°C und 350°C in der Weise verfolgt werden, daß parallel behandelte Proben nach verschieden langer Haltezeit im Salzbad in Wasser abgeschreckt wurden. Hiebei soll der noch nicht in Zwischenstufengefüge umgewandelte Anteil des Austenits in Martensit übergehen, der (besonders bei subjektiver Beobachtung infolge des Farbunterschiedes) im Mikroskop gut unterscheidbar ist, sofern er von den Feldern des Zwischenstufengefüges getrennt liegt. Offen muß aber die Frage gelassen werden, ob nicht, auch bei scheinbar vollständiger Umwandlung in Zwischenstufe, noch Austenitreste in so inniger Vermengung mit dem Zwischenstufengefüge zurückbleiben können, daß sie, trotz der Umwandlung in Martensit bei der anschließenden Abschreckung in Wasser, durch die mikroskopische Gefügebeobachtung allein nicht erfaßt werden; daß dies zutrifft, konnte durch einige Tastversuche mit einem Dilatometer nach Schaaper sehr wahrscheinlich gemacht werden. Danach ist nämlich in jenem Zeitpunkt, in dem die Gefügeausbildung schon auf eine vollständige Umwandlung des Austenits in Zwischenstufe schließen läßt, diese erst zu etwa 90% vollzogen, sodaß also 10% Rest-austenit noch vorliegen. Ein genauerer Nachweis könnte durch Messungen der magnetischen Induktion geschehen, auf die aber im Rahmen dieser Arbeit verzichtet werden mußte. Trotzdem für beide Gußeisensorten für eine Temperatur von 350°C die relativ größte Um-

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wandlungsneigung des Austenits in die Zwischenstufe festgestellt werden konnte, muß also angenommen werden, daß „verborgene" Austenitreste auch bei gefügemäßig scheinbar vollständiger Umwandlung erhalten bleiben. Sie werden dann erst währernd der Verschleißbeanspruchung selbst, sofern diese mit einer genügend starken Kaltverformung (Verquetschung) der Oberflächenzone verbunden ist, in Martensit übergehen und zumindestens eine der Ursachen für den hohen Verschleißwiderstand des in bestimmter Weise auf Zwischenstufengefüge vergüteten Gußeisens sein, gemäß den Gedankengängen von DEMIDOWA UND KUNJAWSKI[7]. Eine andere Ursache, die daneben wirksam sein wird, ist aber wohl in der vergleichsweise höheren Zähigkeit des in bestimmter Weise (nämlich wieder bei 350°C) isotherm umgewandelten Gußeisens zu suchen; es ist bekannt, daß eine höhere Zähigkeit bei gleicher Härte den Verschleißwiderstand verbessert, da sie gleichbedeutend ist mit einer weiteren Verformungsmöglichkeit der verquetschten Oberflächenzone, bevor diese in Form von Schüppchen als „Verschleiß-staub" abreißt[8].

Die Gefügebilderreihen, die das Fortschreiten der isothermen Umwandlung beim Verweilen des Gußeisen-austenits im Salzbad bei 450°C und bei 350°C anzeigen, sind bei einer bestimmten Temperatur und Zeit für die beiden Gußeisensorten sehr ähnlich. Es soll daher als Beispiel nur die Bilderreihe für das Fortschreiten der isothermen Umwandlung bei 450°C für das Gußeisen A in den Abb. 3, 4, 5 und 6, und jene bei 350°C für das Gußeisen B in den Abb. 7, 8, 9 und 10 hier wiedergegeben werden. Abb. 3 und Abb. 7 entsprechen hiebei dem Fall, daß die sogenannte Anlaufzeit für die Zwischenstufenumwandlung noch nicht durchlaufen ist, daß also überhaupt noch kein Austenit isotherm umgewandelt worden ist, so daß nach dem Abschrecken 100% Martensit im Gefüge erzielt wird; Behandlungen, die zu den durch Abb. 3 und Abb. 7 gekennzeichneten Zuständen geführt haben, liegen daher noch vor dem Beginn der Bildung von Zwischenstufengefüge. Abb. 6 und Abb. 10 liegen am anderen Ende der Reihe und entsprechen dem Zustand der (wenigstens scheinbar) vollständigen Umwandlung des Austenits in Zwischenstufengefüge. Die jeweiligen Haltezeiten der isothermen Umwandlung sind unter den Bildern angegeben.

Gemäß dem Programm waren zum Vergleich mit den zwischenstufenvergüteten Proben weitere Proben durch „gewöhnliche" Vergütung, also durch Abschrecken und nachfolgendes Anlassen, auf die gleiche Härte zu bringen. Es sei hiezu eine vergleichende Gefügebilderreihe für das Gußeisen A wiedergegeben (mit dem Bemerken, daß das Gefüge für das Gußeisen B praktisch gleich aussieht):

Abb. 11 zeigt zunächst den gehärteten, nicht angelassenen martensitischen Zustand; die zugehörige Wärmebehandlung und die erreichte Härte sind aus Abb. 16 zu entnehmen. Abb. 12 und 13 zeigen das Gefüge der völligen isothermen Umwandlung zum Zwischenstufengefüge bei 350° und 450°. Abb. 14 und 15 geben das Gefüge nach gewöhnlicher Vergütung wieder, die so geführt wurde, daß einerseits die Gefüge der Abb. 12 und 14 und anderseits die Gefüge der Abb. 13 und 15 fast genau in der Härte übereinstimmen. Die jeweils zugehörigen Wärmebehandlungen und die tatsächlich erreichten Härten sind aus Abb. 16 zu entnehmen.

Abb. 16 enthält das Ergebnis der vorbereitenden mechanischen Prüfung für das

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Abb. 3. 10 sec Haltezeit, nach Abschreckung 100% Martensit, Rockwell C-Härte = 51.

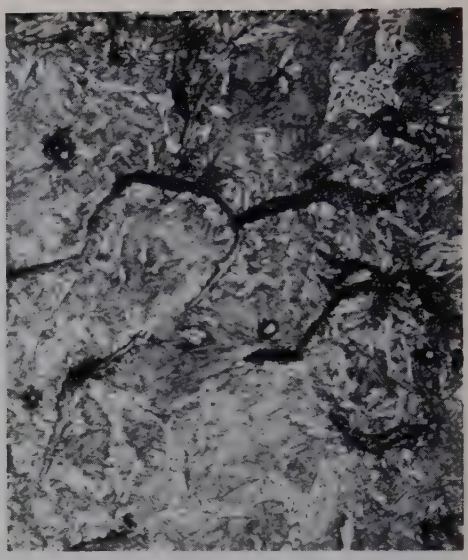

Abb. 4. 100 sec Haltezeit, nach Abschreckung viel Martensit und wenig Zwischenstufe, Rockwell C-Härte = 41.

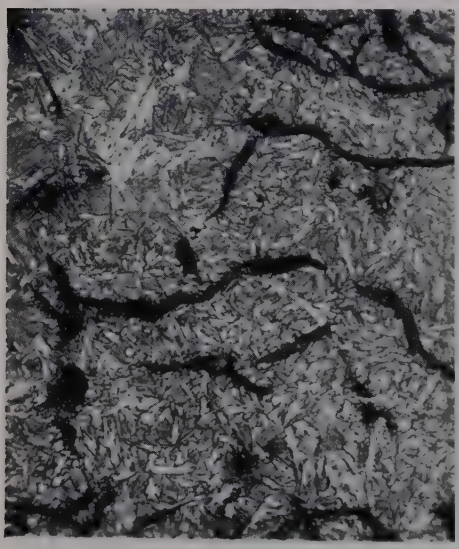

Abb. 5. 300 sec Haltezeit, nach Abschreckung wenig Martensit und viel Zwischenstufe, Rockwell C-Härte = 33.

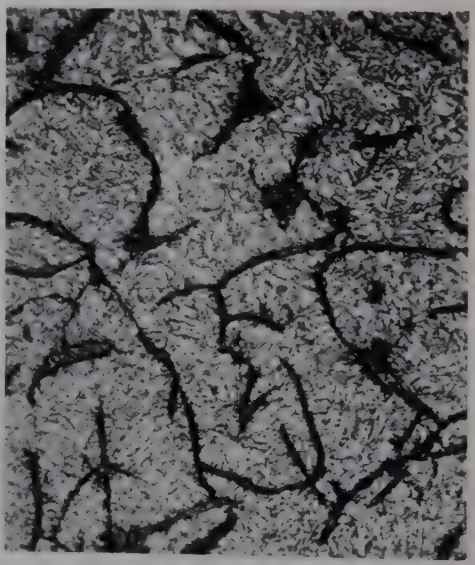

Abb. 6. 1500 sec Haltezeit, nach Abschreckung (scheinbar) 100% Zwischenstufe, Rockwell C-Härte = 26.5.

Abb. 3-6. Gußeisen „A", Isotherme Umwandlung bei 450°C; (× 600).

Abb. 7. 10 sec Haltezeit, nach Abschreckung 100% Martensit, Rockwell C-Härte = 50.

Abb. 8. 30 sec Haltezeit, nach Abschreckung fast 100% Martensit, noch sehr wenig Zwischenstufe, Rockwell C-Härte = 50.

Abb. 9. 300 sec Haltezeit, nach Abschreckung wenig Martensit und viel Zwischenstufe, Rockwell C-Härte = 36.

Abb. 10. 1000 sec Haltezeit, nach Abschreckung (scheinbar) 100% Zwischenstufe, Rockwell C-Härte = 32.

Abb. 7-10. Gußeisen „B", Isotherme Umwandlung bei 350°C; (× 600).

Abb. 11. Gußeisen „A": Martensitischer Zustand nach Abschreckung in Öl, nicht angelassen (× 600).

Gußeisen A im Ausgangs-(Guß-)Zustand und nach verschiedenen Wärmebehandlungen, deren Kennziffern angeführt sind. Die Untersuchung beschränkte sich auf die Bestimmung der Brinell- und Rockwell-C-Härte, sowie der Biegebruchfestigkeit und der bis zum Bruch erreichten bleibenden Durchbiegung (bestimmt an Stäben mit 12 mm Durchmesser und bearbeiteter Oberfläche, aufgelegt auf Stützen von 120 mm Entfernung und in der Mitte zwischen beiden belastet). Abb. 17 gibt die analogen Ergebnisse für das Gußeisen B wieder. Beide Bilder lassen erkennen, daß für beide Gußeisensorten die isotherme Umwandlung (Zwischenstufenvergütung) in der sogenannten „unteren" Zwischenstufe bei 350°C die besten Ergebnisse liefert, d. h. das günstigste Verhältnis zwischen der Härte und Biegefestigkeit einerseits und der als Durchbiegung gekennzeichneten Zähigkeit anderseits. Die Verbesserung gegenüber einer gewöhnlichen Vergütung auf die gleiche Härte ist deutlich. Hingegen bringt eine Zwischenstufenvergütung bei 450° (also im Bereich der sogenannten „oberen" Zwischenstufe) in diesem Belang keinen nennenswerten Vorteil.

Für die eigentliche Aufgabe, nämlich die vergleichenden Verschleißversuche, wurde die von WALZEL UND WERNER[9] angegebene Verschleißprüfmaschine verwendet (Abb. 18). Der Prüfkörper wird hiebei unter einem festgeklemmten Zylinder von 18 mm Durchmesser aus einem gehärteten und polierten Kaltwalzenstahl, der mit 37.5 kg belastet ist, hin- und hergezogen. Die Zahl der Hin- und Hergänge (die Hubzahl) wurde mit 18 je Minute gewählt. Es erfolgt zwischen dem Prüfkörper und dem Gegenkörper eine annähernd lineare Berührung mit trockener gleitender Reibung. Aus der

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Abb. 12. Zwischenstufenvergütet (isotherm umgewandelt bei 350°C, 25 min = 1500 sec)
Rockwell C-Härte = 32
Brinellhärte = 296 kg/mm².

Abb. 13. Zwischenstufenvergütet (isotherm umgewandelt bei 450°C, 30 min = 1800 sec)
Rockwell C-Härte = 25,5
Brinellhärte = 256 kg/mm².

Abb. 14. Gewöhnlich vergütet (von 900°C in Öl abgeschreckt, 1 Stunde bei 520°C angelassen)
Rockwell C-Härte = 33
Brinellhärte = 310 kg/mm²

Abb. 15. Gewöhnlich vergütet (von 900°C in Öl abgeschreckt, 45 min bei 600°C angelassen)
Rockwell C-Härte = 26,5
Brinellhärte = 261 kg/mm²

Abb. 12-15. Gußeisen „A", Zwischenstufenvergütung und gewöhnliche Vergütung auf jeweils die gleiche Härte (× 600).

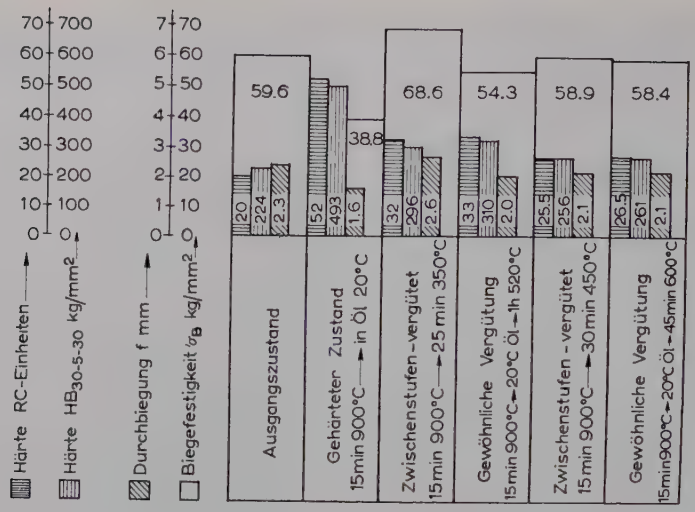

Abb. 16. Mechanische Eigenschaften nach verschiedenen Wärmebehandlungen. Gußeisen „A".

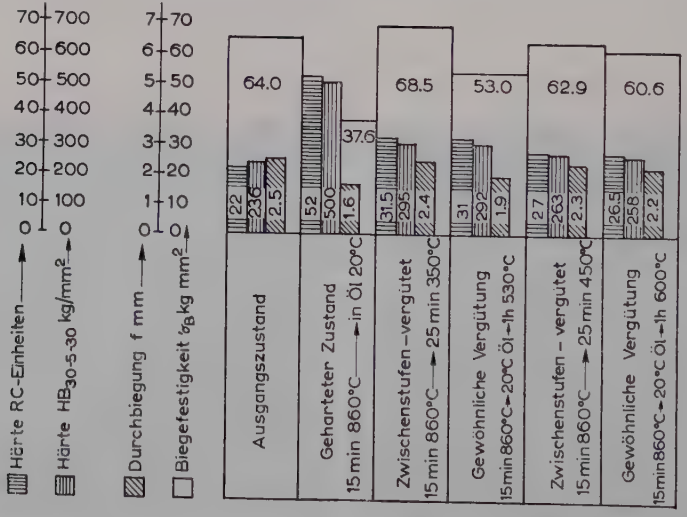

Abb. 17. Mechanische Eigenschaften nach verschiedenen Wärmebehandlungen. Gußeisen „B".

Versuchsanordnung gemäß Abb. 18 ist auch zu entnehmen, daß an den eigentlichen Probekörper mit den Abmessungen 20 × 30 × 60 mm rechts und links in gleicher Ebene zwei weitere Abschnitte aus dem gleichen Werkstoff angeschlossen wurden; für die Auswertung wurden diese aber nicht herangezogen, da an ihnen der Richtungswechsel der Bewegung erfolgt und die Gleitgeschwindigkeit sich stark ändert. Bei jedem Versuch wurden zunächst 1000 Hübe zum Einlaufen gegeben und dann erst die Ausgangswägung des Probestückes vorgenommen. Das Ausgangsgewicht beträgt etwa

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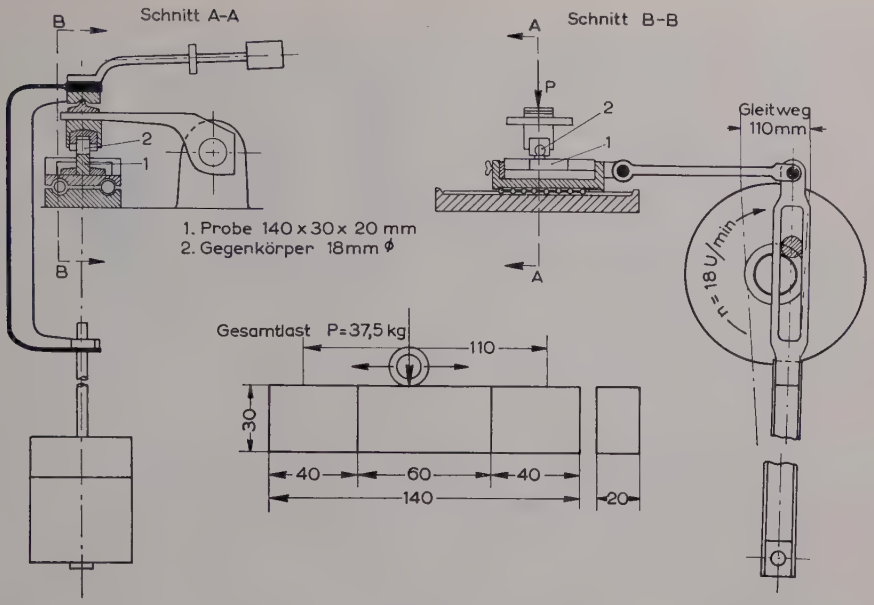

Abb. 18. Verschleißprüfmaschine für gleitende, trockene Reibung nach R. WALZEL und Anordnung der Verschleißproben.

253 g und wird auf 0.001 g genau bestimmt. Es folgen nun 25000 Hübe, die bewertet werden, entsprechend einer Laufzeit von rund 23 Stunden; der Verschleißstaub wird hiebei nicht weggeblasen. Die sodann vorgenommene Schlußwägung ergibt als Differenz zur Ausgangswägung den „Verschleiß", der in Hundertteilen des Ausgangsgewichtes ausgedrückt wird.

Die Ergebnisse der Verschleißversuche sind in Abb. 19 für das Gußeisen A und Abb. 20 für das Gußeisen B dargestellt. Neben dem Verschleiß, der wegen der großen aufgetretenen Unterschiede im logarithmischen Maßstab aufgetragen werden mußte, sind wieder die Brinell- und Rockwell C-Härten eingezeichnet und die genauen Wärmebehandlungen angegeben.

Wie nicht anders zo erwarten, zeigt der martensitische Zustand den geringsten Verschleiß; der Einfluß der hohen Härte überwiegt hier stark den Einfluß der fehlenden Zähigkeit. Gußeisen in diesem Zustand scheidet aber bekanntlich für die große Mehrzahl der Verwendungen aus.

Auffallend günstig in jedem Belang liegen aber die durch isotherme Umwandlung bei 350°C auf Zwischenstufengefüge gebrachten beiden Gußeisensorten. Die wesentliche Erhöhung des Verschleißwiderstandes (d.h. die Verminderung des Verschleißes) gegenüber den durch gewöhnliche Vergütung auf die gleiche Härte gebrachten gleichen Gußeisen ist offensichtlich und bei beiden Sorten anteilig etwa gleich groß; *der Verschleißwiderstand ist etwa auf das 20-fache erhöht.* Damit sind die Angaben im Schrifttum grundsätzlich bestätigt. Die ziffernmäßigen Ergebnisse sind, wie früher erwähnt, aber zweifellos auch stark durch das angewendete Verschleißprüfverfahren beeinflußt; sie

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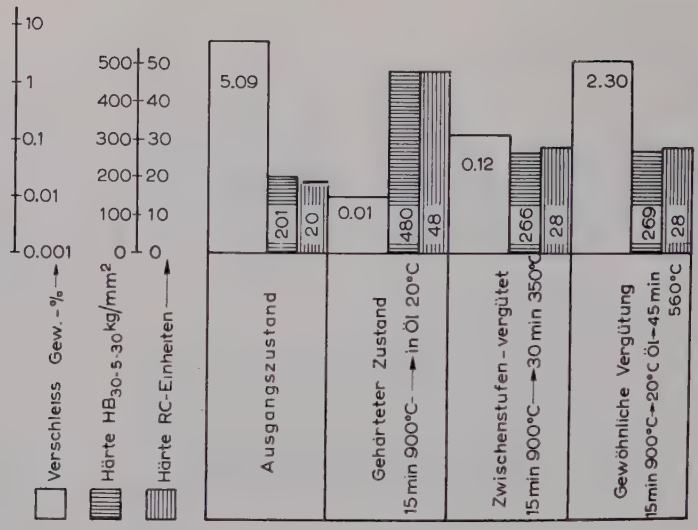

Abb. 19. Verschleißfestigkeit nach verschiedenen Wärmebehandlungen. Gußeisen „A".

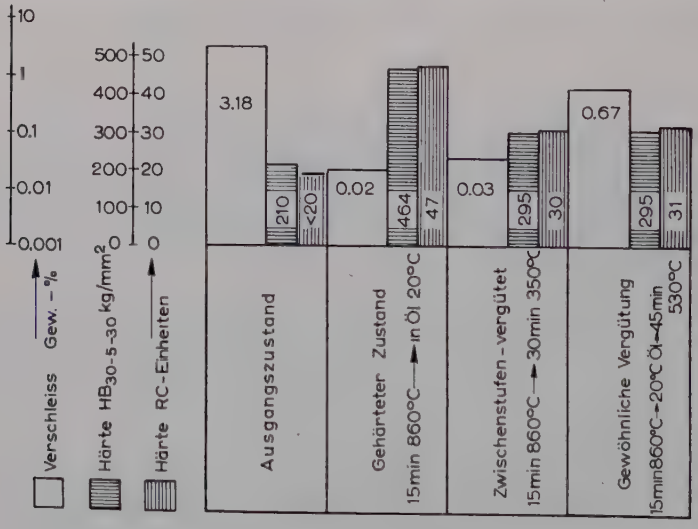

Abb. 20. Verschleißfestigkeit nach verschiedenen Wärmebehandlungen. Gußeisen „B".

würden z.B. voraussichtlich schon anders liegen, wenn man nicht gehärteten Stahl auf Gußeisen, sondern Gußeisen auf Gußeisen reiben lassen würde, wie dies für den Kolbenring und die Zylinderbüchse zutrifft. Es ist aber zu erwarten, daß die *Richtung* der Vergleichswerte von zwischenstufenvergütetem und gewöhnlich vergütetem Gußeisen erhalten bliebe.

Auf eine Verfolgung der Verschleißversuche mit Gußeisen, die bei 450°C isotherm umgewandelt worden waren, konnte verzichtet werden, da Tastversuche ergeben hat-

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ten, daß diese Behandlung keine nennenswerte Verbesserung gegenüber der gewöhnlichen Vergütung auf gleiche Brinell-härte bringt; dies hatte sich im übrigen auch schon im Verhältnis der Zähigkeit zur Härte gezeigt. Es muß also nochmals betont werden, daß nur mit einer bestimmten Art der Zwischenstufenvergütung ein Vorteil zu erreichen ist und das Optimum in ziemlich engen Temperaturgrenzen liegen dürfte. Offenbar sind diese aber auch abhängig von den Abmessungen der Gußeisenstücke und vom Legierungsgehalt; eine Verfolgung dieser Abhängigkeiten muß einer späteren Untersuchung vorbehalten bleiben. Z.B. zeigten sich schon merkliche Unterschiede, wenn Stäbe mit 12 mm Durchmesser und 120 mm Länge, oder Stäbe 30 × 20 × 60 mm der isothermen Behandlung unterzogen wurden, ohne daß hier auf Einzelheiten eingegangen werden kann. Wir sind im übrigen der Meinung, daß nach unserem Beitrag weitere Untersuchungen zu dem praktisch zweifellos wichtigen Problem des Verschleißwiderstandes von Gußeisen mit Zwischenstufengefüge durchaus erwünscht sind.

Es ist uns eine angenehme Pflicht, der Tiroler Röhren- und Metallwerke Aktiengesellschaft in Solbad Hall in Tirol, die in großzügiger Weise diese Untersuchungen gefördert hatte, hier unseren besonderen Dank zu wiederholen.

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Eingegangen am 21. August, 1957

DIAGNOSIS AND ANALYSIS OF PLAIN BEARING FAILURES*

P. P. LOVE

The Glacier Metal Co. Ltd., Wembley (England)

SUMMARY

Failure of a bearing is due to faulty design, faulty manufacture, faulty assembly or faulty use. Each of these aspects is considered in turn, although they cannot always be entirely separated. A number of bearing failures are illustrated, and references are given to some sources of design information.

ZUSAMMENFASSUNG

Das Versagen eines Lagers kann an Fehler im Entwurf, in der Lagerherstellung, in der Lagermontage oder im Gebrauch eines Lagers zugeschrieben werden. Jede dieser Möglichkeiten wird analysiert obwohl sie nicht immer auseinander gehalten werden können. Eine Anzahl von Lagerversagern wird abgebilded und ein Hinweis auf die Literatur für Lagerkonstruktion wird gegeben.

INTRODUCTION

In machinery a bearing is that locality at which force is transmitted from one element to a second element moving relatively to the first. A *plain bearing* is a part of construction adapted to transmit force to a co-operating part sliding on or within it. This is a formal definition of a plain bearing which includes "bushes", "brasses", "sliders", "bearing liners", etc., and excludes what are generally known as ball and roller bearings. The definition places no limitation on the conditions of operation, but in this paper it should be assumed that oil is normally present as a lubricant. Because of the great variety of plain bearings the paper will be limited to consideration of journal or cylindrical bearings.

Like any part of construction, a plain bearing has to be designed, manufactured and assembled or fitted in position before it can be used. It follows, therefore, that if the bearing fails it can only do so for any of the following reasons:

(i) faulty design,
(ii) faulty manufacture,
(iii) faulty assembly,
(iv) faulty use.

* Lecture issued as preprint and read at a meeting of the Institution of Engineers and Shipbuilders in Scotland on April 16th, 1957. To be published as paper No. 1225 in the Proceedings of that Institution. This paper is a slightly modified version of the preprint published by permission of the Institution.

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It is proposed to consider each of these aspects in turn but it will be appreciated that interactions exist between them, for example, manufacturing methods can influence design almost as much as the requirements of use.

DESIGN

There is considerable literature[1-4] on the design of plain bearings for those who wish to study the subject. In spite of the number of papers and books on the subject, however, bearing design is a routine procedure only for simple cases where, for example, the load to be carried is constant in magnitude and direction and the sliding speed is of the order of up to 50 ft. per sec. Certain particular cyclic or rotational loading conditions have been examined and analysed but these are only occasionally encountered in practice. For example, SWIFT AND NEWKIRK[1] have each shown that a journal running at ω r.p.m. in a cylindrical bearing cannot sustain hydrodynamically a load rotating at $\omega/2$ r.p.m. Such oil film breakdown is experienced when a turbine is made to rotate at twice its fundamental critical speed.

Probably the most common of the heavily-loaded bearings are the crankshaft main and connecting-rod big-end bearings of reciprocating internal combustion engines. The nature and effects of the loading on these bearings have not so far been suf-

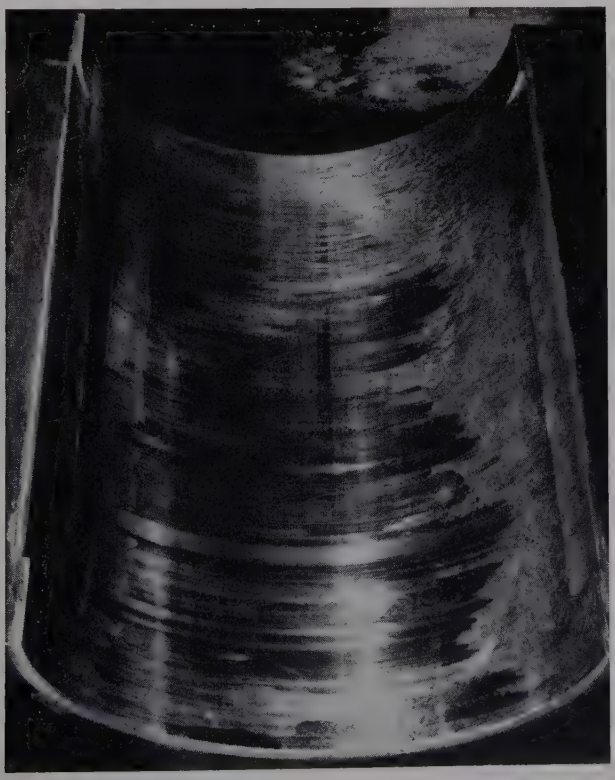

Fig. 1. Bearing failed by "wiping", *i.e.*, surface melting of white-metal.

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ficiently investigated to enable them to be designed fundamentally. Consequently their design to date has been an evolutionary process based on experience, trial and error. In turn, the study of bearing failure is relatively important.

In the early days of design of bearings the product of the load in terms of pressure over the projected area and the relative surface speed was used as the design parameter. This "PV factor" was abandoned because it disregarded hydrodynamic effects and for many years, until very recently, pressure alone was the design parameter. Both these parameters were based on "failure" evidence. In the old days when bearings were hand fitted to very close clearances it was observed that bearings "wiped", that is, the white-metal melted on the surface of the bearing and moved round with the journal until it was squeezed out of the way. There was a rough correlation between this wiping and the PV factor. Fig. 1 is an example of such a failure. This type of failure rarely occurred, however, when the bearing was designed with a clearance of the order of 0.001 in. per in. of diam. and designers were able to increase bearing loads until a new type of failure was observed, namely, fatigue of the white-metal as shown in Fig. 2. It was found

Fig. 2. Bearing failed by fatigue, *i.e.*, progressive cracking of white-metal under mechanical stress.

that if the maximum load on the bearings of engines approached 2,000 lb. per sq. in. (140 kg/cm^2) of projected area the incidence of such failures became significant and for the last 25 years this has been regarded as the practical limit of a conventional white-metal-lined bearing. During that period, however, certain concepts, separately by F. P. BOWDEN of Cambridge and the technical staff of Albion Motors Ltd., led to the use of very thin layers of soft metal over or supported by a harder or stronger metal. It was ultimately broadly established, mainly on experimental work carried out by the Cleveland Graphite & Bronze Co. and by General Motors, both of the United States of America, that the load-carrying capacity of white-metal could be doubled if its thickness

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bonded to steel was of the order of 0.002 in. (0.05 mm) as distinct from 0.030 in. (0.75 mm). The manufacture of bearings with such thin white-metal is not easy, but with present-day manufacturing techniques thickness limits of 0.003 to 0.006 in. (0.075 to 0.150 mm) are practicable and such bearings can carry about 50% more load than bearings with white-metal thickness in excess of 0.012 in. (0.3 mm).

In recent years, however, it has become apparent that maximum pressure is not a particularly good parameter because in some engines white-metal-lined bearings have consistently failed at as little as half the pressure at which almost identical bearings have operated successfully in other engines. In the engineering research department of the Author's company white-metal-lined bearings have operated indefinitely subject to fluctuating loads peaking at 6,000 lb. per sq. in. (420 kg/cm^2). This is reduced to about 2,500 lb. per sq. in. (175 kg/cm^2) if the shaft is sloped 0.001 in. per in. relative to the axis of the bearing. Crankpin and journal slopes of this order are not uncommon in engines of about 100 h.p. at 3,500 r.p.m. A preliminary analysis of incidence of bearing fatique failures in various engines indicates that the ratio of crankpin diameter to crankshaft journal diameter is significant. The greater this ratio the less the incidence of bearing fatigue failure, other things being equal. This applies both to big-end bearings and main bearings.

It is well known that one of the principal reasons for using the soft, low melting-point metals for lining bearings is that in the event of failure they will break down without initially causing serious damage to the co-operating journal, which would be much more costly to replace. The strengths of the various white-metals in common use fall with rise of temperature and hence the load-carrying capacities also fall with rise of temperature. The main source of heat in a bearing is derived from the work done in shearing the oil in the clearance space, and therefore oil viscosity is a major factor. This is doubly so because the thinner the oil the greater the flow of the oil through the clearance space and therefore the more heat is carried away. By and large the oil viscosity in most engines is higher than desirable. Many engines running with SAE 30 oil would be better both as regards frictional losses and incipient bearing failure if an SAE 20 or even an SAE 10 oil were used. The real low limit of oil viscosity tolerable is more likely to be determined by the performance (as regards wear) of tappets than by any extreme bearing condition.

Yet another factor in the performance of a bearing is the relative angular velocity of the load vector. There is evidence indicating that loads rotating at half journal speed even for such short periods as 50° of journal rotation are sufficient to reduce the thickness of the oil film to such an extent that the high rate of shear causes surface temperatures which result in bearing failure. Thus the relative mass centered at the big end compared with the mass of the piston and small end can affect the load-carrying capacity of the big-end bearing.

A bearing may fail because it is not designed to withstand the conditions causing wear. This is a very rare type of failure because it is detected and rectified at the design stage, but it is mentioned here because such factors as bore/stroke ratio are statistically significant. The greater this ratio the less the wear. One explanation privately com-

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Fig. 3. Bearing failed as a result of unsuitable grooving — grooves have reduced the bearing area in a loaded region sufficiently to cause fatigue.

municated to the Author by Mr. A. E. Burke follows on recently published work[5,6] on the oil film thicknesses measured between piston rings and cylinder bores. Generally speaking, the greater the bore/stroke ratio the less the piston speed, and the thinner the mean oil film between piston ring and cylinder bore, in turn, the smaller the abrasive particles metered from the cylinder combustion space into the crankcase and hence the less the wear.

It will therefore be appreciated that the single design parameter has been displaced by a complex of factors. Unfortunately, so little is known of the quantitative effects of these or of their interactions that the engine designer at present has still to rely almost entirely on trial. The effect of this procedure, however, is that relatively few bearings fail because of *inadequate* design. Unsuitable grooving as shown in Fig. 3 is probably the most common design fault.

MANUFACTURE

Millions of plain bearings are made each week by the manufacturers of plain bearings in Great Britain. It would be surprising if they were all perfect but, nevertheless, failures

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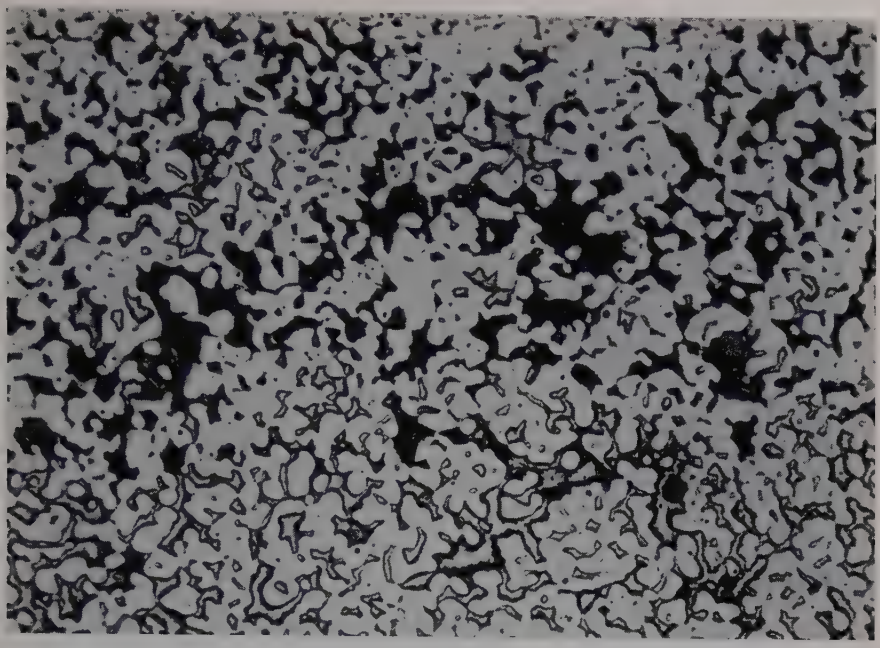

Fig. 4. Micro-section of faulty sintered copper-lead; black areas show porosity.

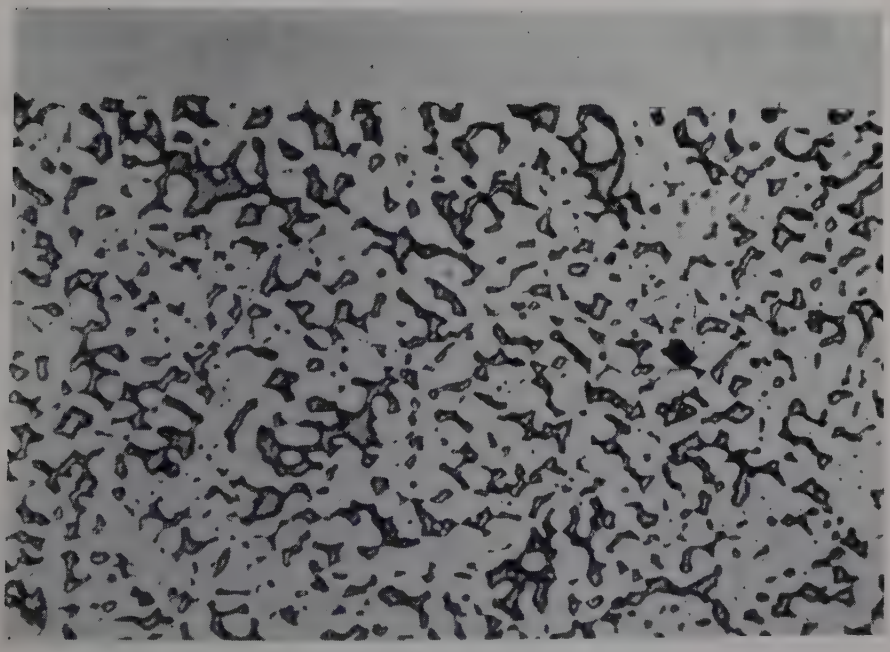

Fig. 5. Micro-section of sound copper-lead.

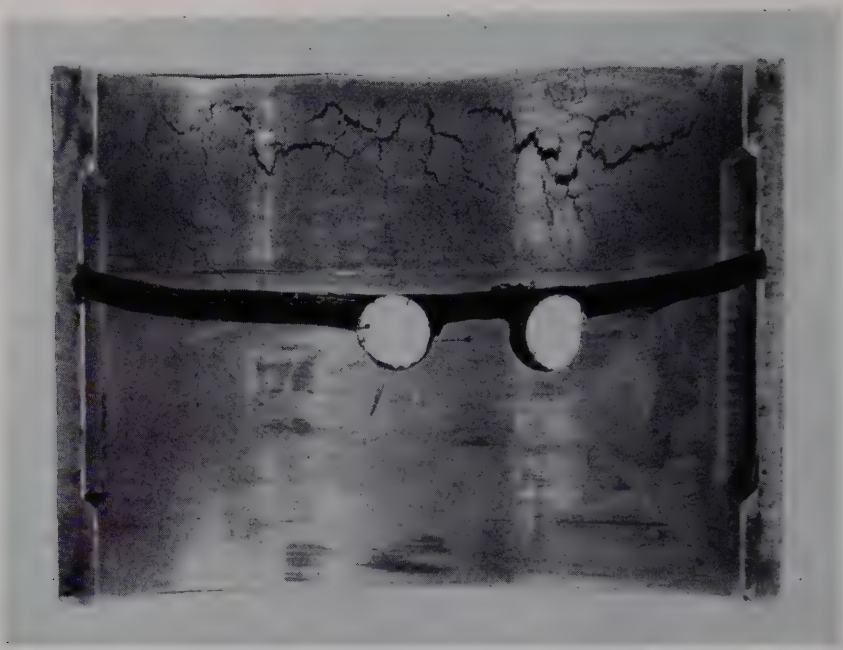

Fig. 6. Steel-backed white-metal-lined bearing which was re-lined, and subsequently failed because of defective bond; observe the cracks and the local parting of the white-metal from the back.

due to faulty manufacture are relatively rare and these are usually detected on engine test. The very large numbers of bearings produced enable the manufacturer to operate very rigorous controls over the processes of manufacture. These processes are (*a*) metallurgical and (*b*) sizing. The metallurgical processes are more difficult to control because, as a rule, the results can only be measured by testing to destruction. Metallurgical processes are carried out either on individual bearings or on strip material which is subsequently formed into bearings. In the former, control of the process can be checked only by destroying a sample number of bearings from each batch. This is costly, and consequently the standard of individually processed bearings cannot be as high as that of bearings made from processed strip which is the subject of statistically designed controls on bond strength between lining and steel backing, tensile strength of lining, microstructure, and so on. Figs. 4 and 5 show micro-sections of porous and sound copper-lead. Present-day controls on strip materials are such that the probability of a materially defective bearing getting into an engine is less than 1 in 50,000.

Of individually lined bearings, control of the bond between the white-metal and the steel backing is the least simple. The loads imposed on bearings are such that considerable shear stresses exist at the junction between the white-metal and the steel backing. If the bond is faulty the white-metal may not be adequately supported by the steel and failure may ensue, as illustrated in Fig. 6.

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ASSEMBLY

Faults in assembly or fitting can give rise to a variety of failures. With modern thin-walled bearings cleanliness is important. A small particle of grit or metal trapped between the back of the bearing and the housing into which it is fitted can produce a heavily loaded spot in the bore of the bearing. Heat produced at this spot is substantially insulated from the housing by the space around the particle and on this account too is likely to cause a bearing failure. Figs. 7 and 8 show an example of an incipient failure of this kind.

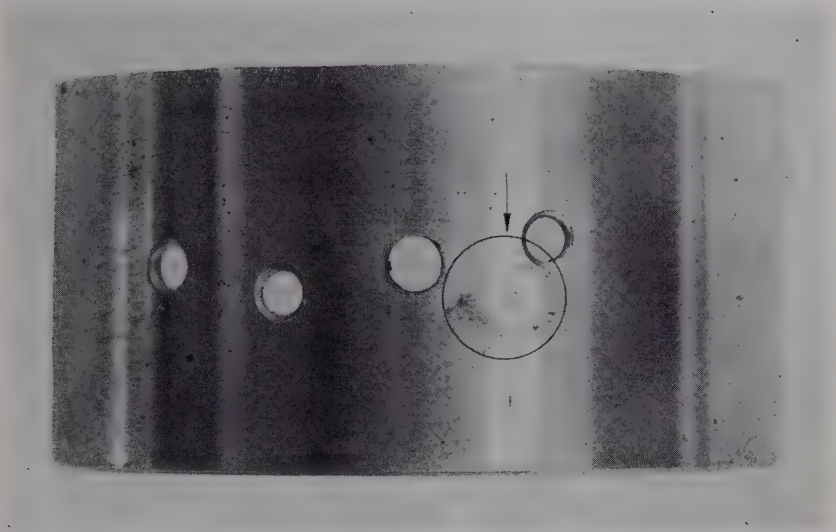

Fig. 7. Back of a bearing which was assembled with a particle of steel between it and the housing.

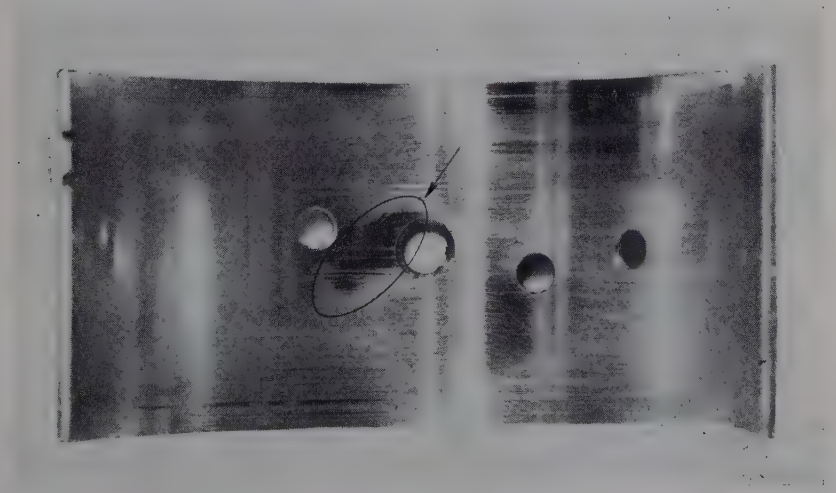

Fig. 8. Bore of the same bearing as Fig. 7, showing how the trapped particle has caused a high spot and incipient failure.

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Fig. 9. Fretting corrosion on the back of a bearing which had been assembled and put into service with insufficient interference fit.

Fig. 10. Bearing which had been assembled and put into service with excessive interference fit; the bearing was crushed near the joint face and the swollen area has failed by fatigue.

Thin-walled bearings rely upon their interference fit within the housing to prevent movement when in operation. If the fit is insufficient fretting corrosion may occur between the back of the bearing and the bore of the housing. Fig. 9 shows the fretting corrosion on the back of a bearing which had been assembled with insufficient interference fit. If the bearing is assembled with excessive interference fit the bearing may be crushed near its joint face as shown in Fig. 10.

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Occasionally there are cases of grossly bad assembly or assembly conditions. Fig. 11 shows the bore of a failed bearing, Fig. 12 the back of that bearing, and Fig. 13 the bore of the connecting rod into which the bearing was assembled.

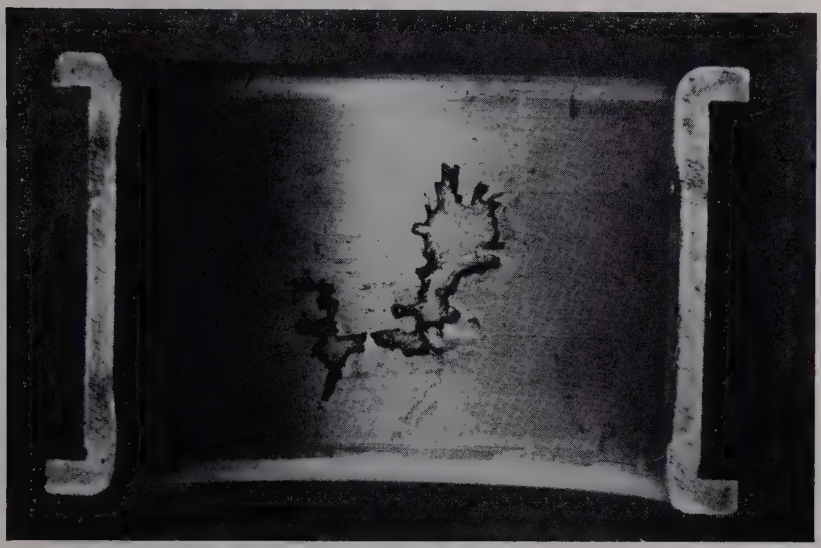

Fig. 11. Bore of failed bearing (see Figs. 12 and 13).

Fig. 12. Back of same bearing as Fig. 11.

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Fig. 13. Bore of connecting rod into which the bearing (Figs. 11 and 12) had been fitted; the grossly damaged connecting rod caused the bearing to fail.

USE

Bearings failing by misuse can be grouped into those which fail owing to neglect on the part of the user or those which fail owing to some new condition which fortuitously comes into operation.

Certain commercial vehicle engines are governed to predetermined maximum speeds. It is possible, however, to exceed these speeds by running downhill with the engine in a low gear. If the engine is indiscriminately speeded up by opening the throttle (or like act) in such circumstances it is possible to impose excessive inertia loads on the bearings and so cause failure. Fig. 14 shows a pair of main bearings from a heavy goods vehicle which operated between Sheffield and Manchester. It was established that the engine of the vehicle was frequently driven down fairly steep inclines in bottom gear.

The use of a fuel of high sulphur content in combination with cold weather or unusually short journeys may result in the lubricating oil becoming acidic and may cause corrosion to occur. This was not uncommon at one time with certain grades of fuel and oil, and copper-lead bearings as then made were caused to fail in the way shown in Figs. 15 and 16. This type of failure is now rare since copper-lead bearings are corrosion-inhibited and neutralizing additives are included in most of the modern engine crankcase oils.

The failure of a co-operating part, for example, the breakage of a crankshaft, can impose such excessive pounding loads as to result in a bearing failure in a few seconds. Fig. 17 shows how the lining of a copper-lead-lined main bearing was extruded. The engine crankshaft had fractured. Fig. 18 is a laboratory bearing that failed similarly after running for 15 sec at load intensities estimated to be similar to that imposed in the bearing shown in Fig. 17.

The inadvertent entry of large dust particles into the lubricant can result in erosion as shown in Fig. 19.

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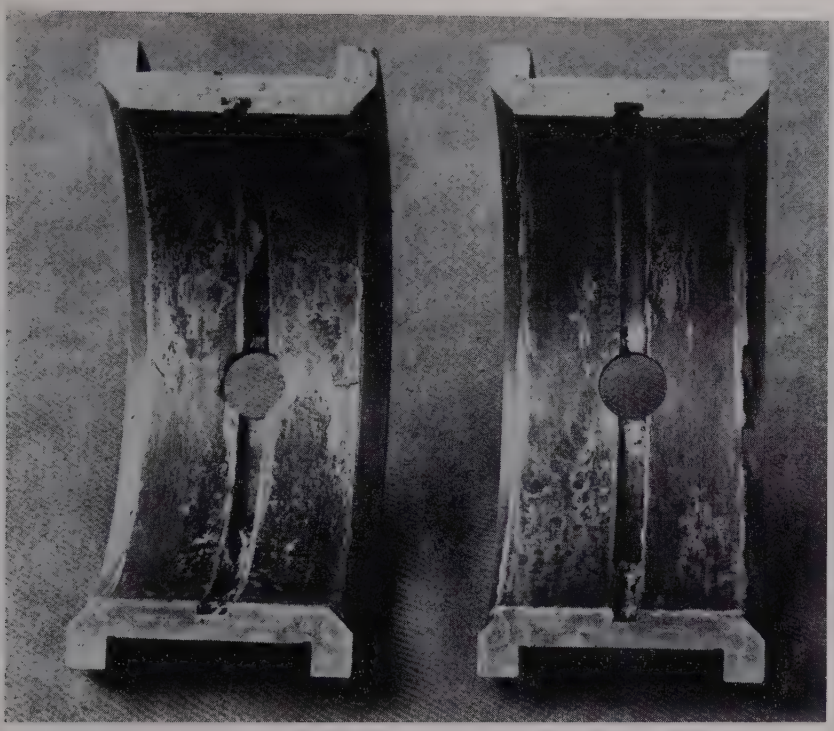

Fig. 14. Pair of main bearings from a heavy goods vehicle engine which failed because the engine was frequently run above its governed maximum speed.

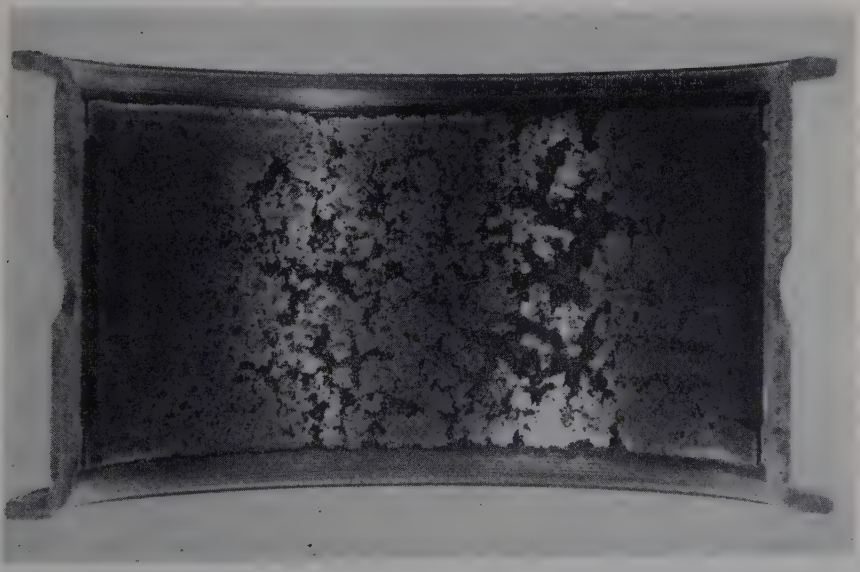

Fig. 15. Corrosion in a copper-lead bearing caused by acidic lubricating oil (see Fig. 16).

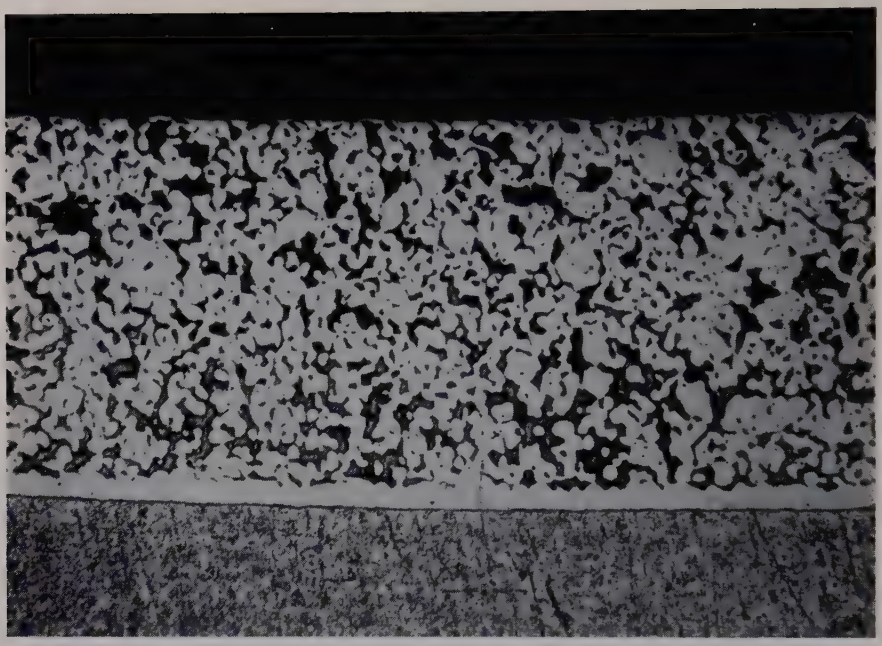

Fig. 16. Micro-section of a bearing with corrosion damage similar to that in Fig. 15; observe the depth to which lead has been removed from the copper-lead.

Fig. 17. Bearing failure which followed the fracture of an engine crankshaft; the resulting excessive loads have extruded the copper-lead lining from the bearing.

Fig. 18. Bearing failed in a laboratory test after running for 15 sec at a load estimated to be similar to that imposed on the bearing in Fig. 17.

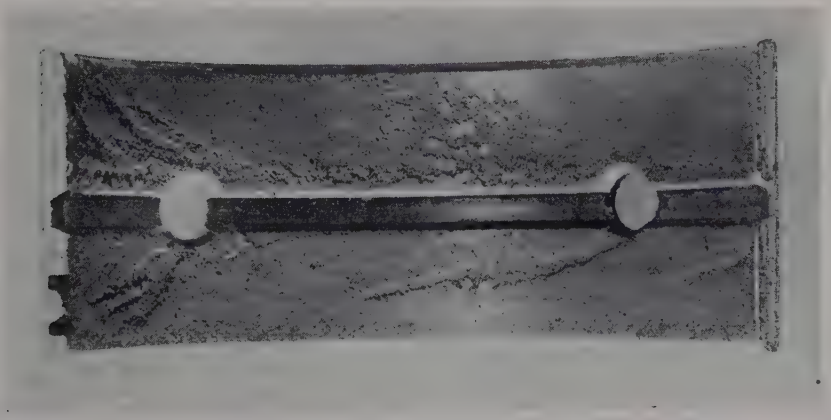

Fig. 19. Erosion of a bearing caused by the inadvertent entry of large solid particles into the lubricant.

CONCLUSION

A number of failures occur for which no clear explanation can be found. This fact confirms the view that knowledge of the behaviour of bearings subject to other than fairly simple load/time patterns is still scanty. By design white-metal-lined bearings

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can carry much greater loads than are at present successfully applied, and correspondingly greater loads could be carried by other bearing alloys such as copper-lead and aluminium-tin. Non-metallic materials are also in the picture but the best use of all of these will only be made when the operation of bearings under complex load/time patterns is explored and understood.

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Received for review May 1, 1957
Accepted August 28, 1957

NORMUNG AUF DEM VERSCHLEISSGEBIET?

H. WAHL*

Stuttgart (Deutschland)

SUMMARY

A condensed version in English is given at the end of this paper.

A. ALLGEMEINES

Im allgemeinen denkt man an Normung erst in der Endphase einer technisch-wissenschaftlichen Entwicklungsarbeit. Man normt Gegenstände, Werkstoffe, Verfahren oder Bezeichnungen meist erst *nach* Überwindung der grundsätzlichen Entwicklungsschwierigkeiten, nach Erreichung einer guten Einsicht in die auf dem betreffenden Gebiet vorliegenden Einflüsse und ihre Wirkungen, nach Kenntnis der verschiedenen Lösungsmöglichkeiten und deren Vor- und Nachteilen. Vielfach ist die Normung geradezu der Abschluss einer langjährigen Entwicklungsarbeit.

Wie passen zu solchen Feststellungen die Bestrebungen eines deutschen Arbeitskreises, Normung auf dem Verschleissgebiet zu betreiben? Es besteht doch nicht einmal eine einheitliche Auffassung über den Begriff „Verschleiss", ebensowenig über eine gute Systematik des Verschleissgebietes. Man ist noch kaum in der Lage, einen speziellen Verschleissfall klar (zahlenmässig) zu definieren und ihn von anderen Verschleissfällen abzugrenzen. Es existieren zwar schätzungsweise 20,000 oder mehr Veröffentlichungen über wissenschaftliche oder praktische Verschleissfragen — aber nur wenige gesicherte Gesetzmässigkeiten auf dem ganzen Verschleissgebiet. Gleicht der Stand unserer Erkenntnisse vom Verschleiss nicht etwa einem ungeordneten Haufen bunter Steine? Ist die bisherige Bearbeitung des Verschleissgebietes, im Ganzen gesehen, nicht sehr unrationell verlaufen?

Trotzdem sprechen vielleicht zwei wichtige Gründe *für* eine *beschränkte* Normungsarbeit auf dem Verschleissgebiet:

(1) Es besteht offensichtlich die Aufgabe, aus dem vorerwähnten „Haufen bunter Steinchen" ein Mosaik zu formen, eine *systematische* Zusammenfassung unserer heutigen Teilerkenntnisse. Dazu bedarf es der Beschäftigung mit allgemeinen Ordnungsfragen auf dem Verschleissgebiet; allgemeine Ordnung aber ist geradezu das Wesen

* Obmann des Arbeitsausschusses D 4 b für Verschleissfragen des Fachnormenausschusses Materialprüfung im Deutschen Normenausschuss.

der Normungsarbeit. Man könnte sich von solcher ordnenden Normungsarbeit auf dem Verschleissgebiet sehr wohl eine wesentliche Steigerung des Gesamtwirkungsgrades der künftigen Bearbeitung dieses Gebietes erhoffen — wenn es gelänge, gute Ordnungsrichtlinien zu finden und diesen eine gewisse Beachtung bei den sachbearbeitenden Stellen zu verschaffen.

(2) Der Vergleich unserer Erkenntnisse über Verschleiss mit einem ungeordneten Haufen bunter Steine erscheint nur teilweise richtig. Eher gleicht das Verschleissgebiet heute einem Mosaik-Torso: Auf einzelnen Teilgebieten kristallisieren sich heute in der Forschung und in der Praxis übereinstimmende, sich vielfach wiederholende Gesetzmässigkeiten heraus. Zum Beispiel gilt dies für das wirtschaftlich besonders wichtige Teilgebiet des Verschleisses von Metallen durch Mineralien, das ja für die gesamte Industrie der Steine und Erden (also z.B. für die Natursteinindustrie, Zementindustrie, Schamotteindustrie, Ziegelindustrie usw.), für den Bergbau, die Erzaufbereitung, den Tiefbau, für die gesamte übrige Hartzerkleinerung, Landwirtschaft usw. eine vordringliche praktische Bedeutung hat. Hier drängt das unmittelbare praktische Bedürfnis grosser Industrien in Richtung der Normung brauchbarer Prüfmethoden für die Verschleissfestigkeit von Werkstoffen einerseits, für die Schleifschärfe von Mineralien andererseits.

Diese Überlegungen bewogen einen Arbeitsausschuss innerhalb des Fachnormenausschusses Materialprüfung (FNM) des Deutschen Normenausschusses, sich seit einer Reihe von Jahren teils mit allgemeinen Ordnungsfragen für das Verschleissgebiet, teils mit Prüfmethoden für durch Mineralien auf Verschleiss beanspruchte Werkstoffe zu befassen. Über diese Arbeiten soll im folgenden auszugsweise berichtet werden; bezüglich der Einzelheiten muss auf die bereits gedruckten bzw. später zu veröffentlichenden Normblätter verwiesen werden*.

B. NORMUNGSARBEITEN ZUR FRAGE DER ALLGEMEINEN ORDNUNG DES VERSCHLEISSGEBIETES

I. DIN-Vornorm 50 320 (Definition des Begriffes „Verschleiss", Analyse von Verschleissvorgängen, Gliederung des Verschleissgebietes)

(a) Der *Begriff* „Verschleiss" wurde nach längeren Beratungen folgendermassen definiert:

„Unter Verschleiss im Sinne der Technik wird die unerwünschte Veränderung der Oberfläche von Gebrauchsgegenständen durch Lostrennen kleiner Teilchen infolge mechanischer Ursachen verstanden".

(b) Der *Analyse von Verschleissvorgängen* wurde folgende Überlegung zugrundegelegt: Ein Verschleissvorgang kann im allgemeinen nur eingeleitet werden, wenn gleichzeitig folgende 5 Anfangsbedingungen („Elemente") gegeben sind (vgl. Abb. 1):

* Erhältlich durch den Beuth Vertrieb G.m.b.H., Köln.

(1) Grundkörper } Verschleiss-Paarung
(2) Gegenstoff }
(3) Zwischenstoff
(4) Bewegung
(5) Belastung.

Ein spezieller Verschleissvorgang wird beschrieben durch möglichst konkrete Kennzeichnung vorstehender 5 Elemente. Diese fünf Grössen bedingen weithin den Ablauf und das Endergebnis jedes Verschleissvorganges. Sie bilden auch die Mittel der praktischen Verschleissbekämpfung.

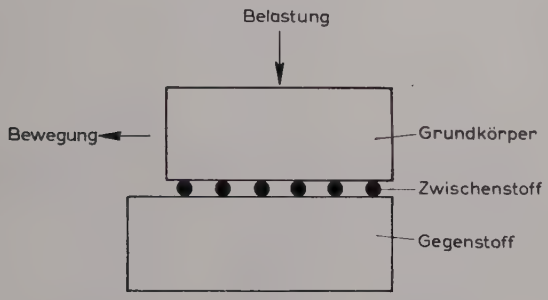


Abb. 1. Die 5 „Elemente" jedes Verschleissvorganges.

(c) *Gliederung des Verschleissgebietes in Verschleissarten:* Unter „Verschleissart" wird eine charakteristische Kombination der 5 Elemente verstanden. Zur Kennzeichnung einer Verschleissart dienen drei Angaben:

(1) Grundkörper (-Werkstoff) : Kurzzeichen gemäss Abb. 2, Tafel I
(2) Gegenstoff : Kurzzeichen gemäss Abb. 2, Tafel II
(3) Übrige Verschl. bedinggn. : Kurzzeichen gemäss Abb. 2, Tafel III

Z.B. bedeutet „Me: Me 3" = Metall: Metall-Trocken-Gleit-Verschleiss eines metallischen Grundkörpers gegen metallischen Gegenkörper, trocken, bei gleitender Bewegung (z.B. Bremsklotz).

II. Norm-Entwurf DIN 50 321 (Messgrössen für den Verschleissbetrag)

Im allgemeinen Sprachgebrauch wird oft „Verschleiss" sowohl im Sinne eines Vorganges, als auch im Sinne eines Betrages verwendet; zur Vermeidung von Missverständnissen wird empfohlen, zwischen „Verschleiss" (als Vorgang) und „Verschleissbetrag" (als Messgrösse) zu unterscheiden. Dabei wird unter Verschleissbetrag ganz allgemein verstanden eine zahlenmässige Angabe über die Änderung der Gestalt eines verschleissenden Körpers.

TAFEL I
SCHREIBWEISE FÜR DEN GRUNDKÖRPER

Benennung	*Kurzzeichen*
Gummi	G:
Holz	H:
Kunststoff	K:
Leder	L:
Metall	Me:
Mineral	Mi:
Textilien	T:
Sonstige Feststoffe	F:

Abb. 2. Unterteilung des Verschleissgebietes (Verschleissarten) nach DIN-Vornorm 50 320.

TAFEL II
SCHREIBWEISE FÜR DEN GEGENSTOFF

Benennung	*Kurzzeichen*
Gummi	G
Holz	H
Kunststoff	K
Leder	L
Metall	Me
Mineral	Mi
Textilien	T
Sonstige Feststoffe	F
Strömende Stoffe (Gase, Dämpfe, Flüssigkeiten evtl. vermischt mit festen Stoffen)	X

BEISPIEL: Me : Mi 3 DIN 50 330

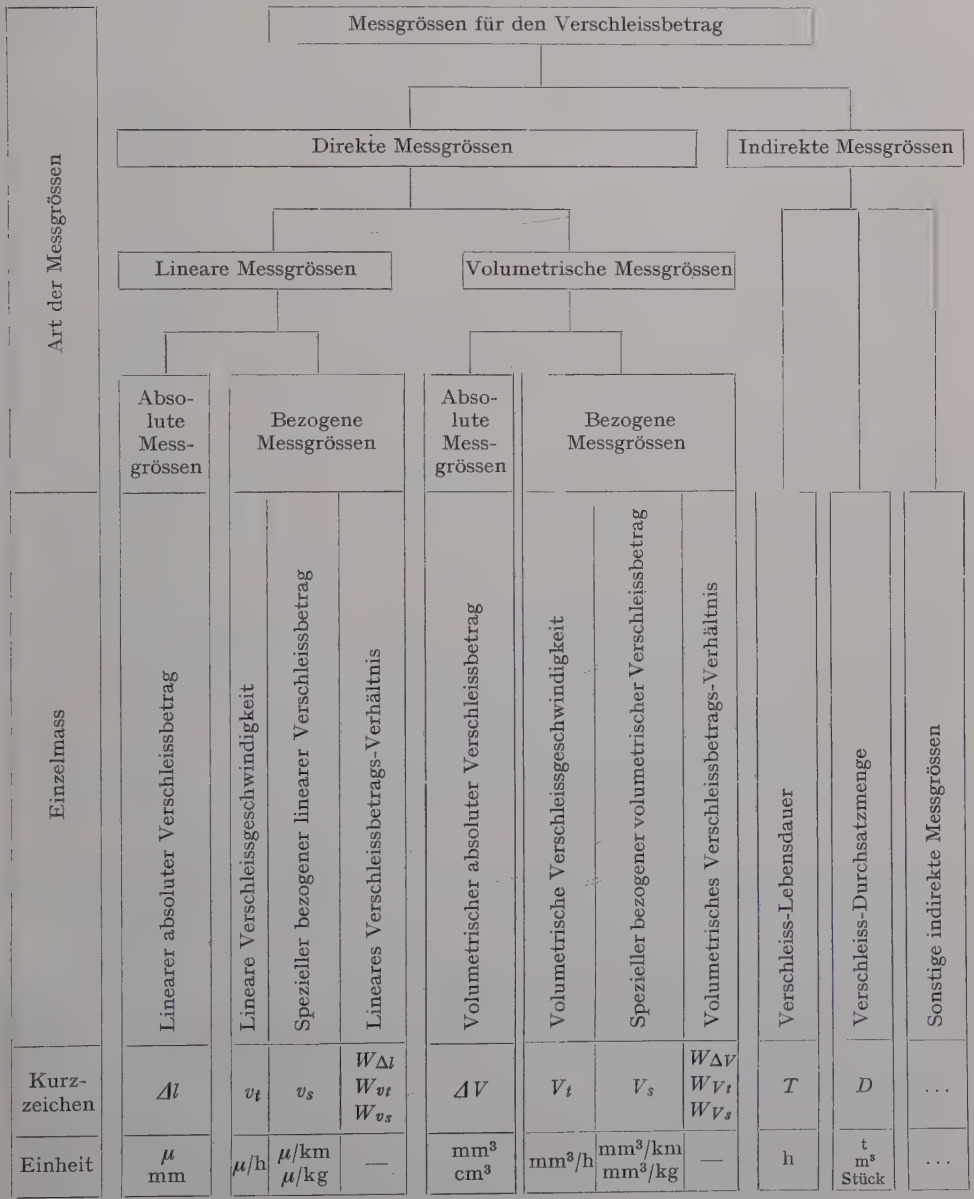
1) Grundkörper ____↑
2) Gegenstoff ____↑
3) Übrige Verschleissbed. ____↑
4) Genormtes Prüfverfahren ____↑

TAFEL III
SCHREIBWEISE FÜR DIE ÜBRIGEN VERSCHLEISSBEDINGUNGEN

Zwischenstoff	*Bewegung*	*Belastung*	*Benennung*	*Kurzzeichen*
flüssig	Gleiten	ruhend oder schwingend	Schmier-Gleit-Verschleiss	1
	Rollen		Schmier-Roll-Verschleiss	2
gasförmig	Gleiten		Trocken-Gleit-Verschleiss	3
	Rollen		Trocken-Roll-Verschleiss	4
fest	Gleiten		Korn-Gleit-Verschleiss	5
	Rollen		Korn-Roll-Verschleiss	6
—	wiederholter Stoss zweier fester Körper		Stoss-Verschleiss	7
—	geschlossene Strömung: parallel / schräg / senkrecht — zur Verschleissflache		Gleit-Strahl-Verschleiss	14a
			Schräg-Strahl-Verschleiss	14b
			Prall-Strahl-Verschleiss	14c
—	Stoss zusammenstürzender Hohlsoggebiete		Sog-Verschleiss	15
	Stoss frei fliegender Flüssigkeitsteile		Tropfenschlag-Verschleiss	16
—	Sonstige		Sonstiger Verschleiss	17

Ein erstes Ziel dieses Norm-Entwurfes ist es, Richtlinien für die Auswahl richtiger Messgrössen für den Verschleissbetrag in den praktisch wichtigeren Fällen zu geben. Zweites Ziel ist es, zu einer besseren Vergleichbarkeit von Veröffentlichungen über Verschleissfragen beizutragen durch Empfehlungen für die Vereinheitlichung der Messgrössen für den Verschleissbetrag.

Abb. 3. Zusammenfassende Übersicht der verschiedenen Messgrössen für den Verschleissbetrag (DIN-Entwurf 50 321)



DIN Entwurf 50 321

Abb. 4. Zusammenfassende Übersicht über die bevorzugten Anwendungsgebiete der verschiedenen Messgrössen für den Verschleissbetrag

\+ bedeutet: anwendbar (+) bedeutet: bedingt anwendbar leere Felder bedeuten: nicht anwendbar

Kennzeichnung des Verschleissfalls				*Direkte Messgrössen*											*Indirekte Messgrössen*		
				Lineare						Volumetrische							
Messmöglichkeit für Gestaltsänderung[1]	Räumliche Verteilung des Verschleissbetrages üb. d. Verschleissfläche	Konstanz der Versuchsbedingungen	Zeitdauer des reinen Verschleissvorganges	absolute	bezogene					absolute	bezogene					Verschleiss-Lebensdauer	Verschleiss-Durchsatzmenge	Sonstige, indirekte Messgrössen
				Δl	v_t	v_s	$w_{\Delta l}$	w_{vt}	w_{vs}	ΔV	V_t	V_s	$W_{\Delta v}$	W_{Vt}	W_{Vs}	T	D	
leicht möglich	gleichmässig	gut	bekannt[2]	(+)	+					(+)	+							
		schlecht (unsicher)	unbek.[3]	(+)		+				(+)		+						
			bekannt[2]					+						+				
			unbek.[3]						+						+			
	stetig veränderlich	gut	bekannt[2]	(+)	(+)					(+)	+							
		schlecht (unsicher)	unbek.[3]	(+)		(+)				(+)		+						
			bekannt[2]					(+)						+				
			unbek.[3]						(+)						+			
	unstetig veränderlich	gut	bekannt[2] unbek.[3]							(+)	+							
		schlecht (unsicher)	bekannt[2] unbek.[3]							(+)		+						
														+				
															+			
Nicht leicht und genau feststellbar oder nicht bevorzugt interess.		mindestens ausreichend	bekannt[2]													+		
			unbek.[3]														+	+

[1] d. h. Möglichkeit der genauen Bestimmung der Änderung der Gestalt des verschleissenden Körpers während des Verschleissvorganges durch Gewichts-, Längen- oder Volumenmessung

[2] bekannt oder leicht feststellbar

[3] unbekannt oder nicht von Interesse oder durch zahlreiche Verschleisspausen unterbrochen.

Es erscheint völlig unmöglich, den Verschleissbetrag in allen Fällen durch eine einzige Messgrösse festzulegen; je nach den Messmöglichkeiten, der Konstanz der Versuchsbedingungen, dem räumlichen Verlauf des Verschleissbetrages über der Verschleissfläche und dem allgemeinen Ziel der Versuche bedarf es vielmehr *verschiedener* Messgrössen, die in Abb. 3 zusammengestellt sind. Abb. 4 enthält eine Übersicht über die bevorzugten Anwendungsgebiete der verschiedenen Messgrössen für den Verschleissbetrag.

III. Beratungsgegenstand 50 322 (Richtlinien für Verschleiss-Versuche)

Auf diesem, noch in Bearbeitung stehenden Teilgebiet soll versucht werden, konkrete Richtlinien sowohl für die Durchführung praktischer *Betriebs*- Verschleiss-Versuche, als auch für die Durchführung von *Modell*-Verschleiss-Versuchen festzulegen.

IV. Beratungsgegenstand 50 323 (Begriffe)

Es soll der Versuch unternommen werden, einige öfters gebrauchte Begriffe und Bezeichnungen zu definieren, um deren einheitliche Anwendung zu fördern. Zum Beispiel sollen etwa folgende Begriffe definiert werden:

(1) Allgemeine Begriffe (Verschleiss, Verschleisswiderstand, Reibungszahl, Härte, Oberflächengüte usw.)
(2) Verschleissbeanspruchung (Elemente, Grundkörper, Gegenstoff, Verschleisspaarung, Zwischenstoff usw.)
(3) Verschleissarten (vgl. Abb. 2, Tafeln I, II, III.)
(4) Verschleissablauf (Fressen, Grübchenbildung, Reiboxydation, Einbettung, Beilby-Schicht, Schälen, Abrieb usw.)
(5) Verschleissmasse (vgl. Abb. 3)
(6) Verschleissprüfung (Modellverschleissversuch, Betriebsverschleissversuch, Verschleissprüfmaschine, Schleifteller, Schleiftopf, Wiederholbarkeit, Vergleichbarkeit, Bewährungsfolge, Differenzierung, Betriebstreue).

C. NORMUNGSARBEITEN ZUR SPEZIELLEN FRAGE DES VERSCHLEISSES VON METALLEN UNTER MITWIRKUNG VON MINERALIEN

I. DIN-Vornorm 50 330 (Verschleiss-Prüfung bei Metall: Mineral-Gleit-Verschleiss, Schleifteller-Verfahren)

Es wird eine Prüfeinrichtung (Abb. 5) vorgeschlagen, bei der die zylindrische Probe stirnseitig gegen einen mit Schleifpapier belegten, rotierenden „Schleifteller" gedrückt und gleichzeitig radial von innen nach aussen bewegt wird; die Probe beschreibt also über dem sich darunter drehenden Teller eine archimedische Spirale.

Die Versuchsdurchführung ist genau festgelegt. Der eigentlichen Hauptprüfung geht eine Vergleichsprüfung voraus, um mit einer Vergleichsprobe (C 60 N) die „Schleifschärfe" des Schleifpapiers zu kontrollieren.

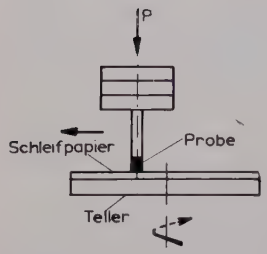


Abb. 5. Schema der Schleiftellerprüfmaschine nach DIN-Vornorm 50 330.

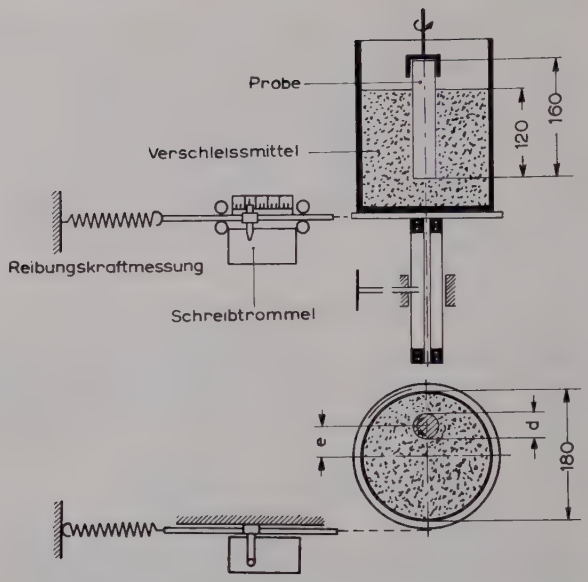


Abb. 6. Vorschlag für eine Schleiftopf Prüfungseinrichtung gemäss Beratungsgegenstand 50 331.

Auch die Auswertung und Darstellung der Ergebnisse wird festgelegt. Als Verschleissmass gilt die auf eine Schleifschärfe 1 und eine Stunde reduzierte Verschleissgeschwindigkeit senkrecht zur verschleissenden Oberfläche.

Das Schleifteller-Verfahren erscheint anwendbar zur Prüfung metallischer Werkstoffe gegen direkten mineralischen Angriff (Metall: Mineral-Gleit-Verschleiss) bei Flächenpressungen bis etwa 5 kg/cm². Dies entspricht etwa der Anwendbarkeit zur Prüfung von Werkstoffen für Bodenbearbeitungswerkzeuge, Förderschnecken und dergleichen. Das Schleifteller-Verfahren ergibt gute Wiederholbarkeit (i.a. $\pm$ 5%), sehr breite Differenzierung (1:50 und mehr zwischen besten und schlechtesten Werkstoffen) und in manchen Fällen nachgewiesene Betriebstreue. Die Anwendung des Schleifteller-Verfahrens ist aber begrenzt durch Verwendung von Schleifpapier als mineralischem Gegenstoff.

II. Beratungsgegenstand 50 331 (Schleiftopf-Verfahren)

Um auch Mineralien als Gegenstoffe verwenden zu können, die nicht in Form von Schleifpapieren vorliegen, wird an der Vereinheitlichung eines zweiten Prüfverfahrens gearbeitet, bei dem die Probe durch einen mit körnigen Mineralien gefüllten „Schleiftopf" bewegt wird. Eine von mehreren zur Diskussion stehenden Prüfeinrichtungen zeigt schematisch Abb. 6. Es soll versucht werden, mit der gleichen Prüfeinrichtung auch in Schleifmittel-Wasser-Gemischen prüfen zu können.

Auch für das Schleiftopf-Verfahren sollen alle Prüfbedingungen genau festgelegt werden. Als Verschleissmass dient entweder die mittlere Dickenabnahme des Probe-

körpers senkrecht zur verschleissenden Oberfläche, bezogen auf 1 km Laufweg, oder die entsprechende Verschleissgeschwindigkeit, bezogen auf eine Stunde Versuchsdauer, oder die Verhältniszahl der Verschleisswerte (d.h. der auf den Vergleichsstahl C 60 N bezogene Verschleiss der Werkstoffprobe).

Das Schleiftopf-Verfahren erscheint geeignet zur Nachahmung solcher Betriebsfälle, bei denen Gleitverschleiss-Beanspruchung unter Mitwirkung von trockenen oder verschieden stark befeuchteten körnigen Stoffen bei geringen Flächenpressungen vorliegt (z.B. Förderrinnen, Rutschen, Bodenbearbeitungswerkzeugen, Rührarmen von Kieswaschanlagen oder Mischmaschinen, Rührwerke usw.)

III. DIN-Vornorm 50 332 (Strahlverschleiss-Prüfung)

Es steht heute fest, dass Strahlverschleiss gegenüber anderen Arten des Verschleisses unter Mitwirkung von Mineralien grundsätzlich verschiedenen Ablauf und verschiedene Wirkungen aufweist; es bedarf deshalb für die Strahlverschleiss-Prüfung auch besonderer Prüfeinrichtungen und Prüfmethoden.

Dabei ist zu berücksichtigen, dass die Art und der Umfang der Zerstörung eines Körpers durch Strahlverschleiss nach den an der Materialprüfungsanstalt der Technischen Hochschule Stuttgart und an einigen anderen Stellen durchgeführten Untersuchungen in sehr hohem Masse von dem *tatsächlichen Anstrahlwinkel* abhängig ist. Die Bewährungsfolge verschiedener Werkstoffe ist je nach Grösse des Anstrahlwinkels völlig verschieden. Deshalb wird empfohlen, auch die Strahlverschleiss-Prüfung bei *verschiedenen* Anstrahlwinkeln durchzuführen und die Ergebnisse in Kurvenform über dem Anstrahlwinkel aufzutragen, wie es z.B. Abb. 7 zeigt.

Unterschieden werden Versuche mit einem weissen Quarzsand (Normalsand mit festgelegten Eigenschaften) für vergleichende Untersuchungen verschiedener Werk-

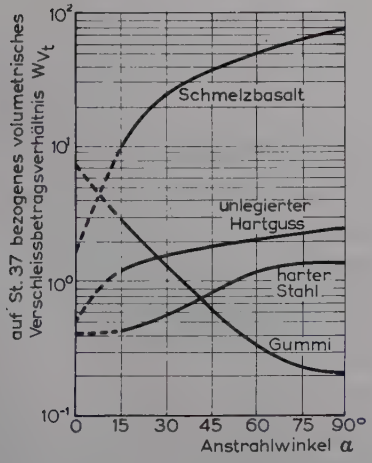


Abb. 7. Einfluss des Anstrahlwinkels bei der Strahlverschleiss-Prüfung.

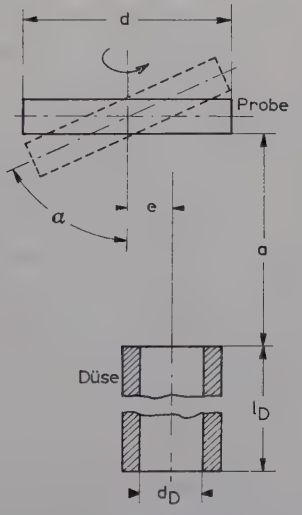


Abb. 8. Strahlverschleiss-Prüfungseinrichtung gemäss DIN-Vornorm 50 332.

stoffe einerseits und Versuche mit beliebigem körnigem Gegenstoff für vergleichende Untersuchungen der Verschleisswirkung verschiedener körniger Stoffe auf einheitlichem Werkstoff andererseits.

Als Prüfeinrichtung ist vorgeschlagen ein Sandstrahlgebläse mit festgelegter Sandstrahldüse. Die Werkstoffprobe bestimmter Abmessungen wird in einer drehbaren Fassung eingespannt, deren Achse exzentrisch zur Achse der Sandstrahldüse versetzt und deren Neigung gegen die Achse der Sandstrahldüse entsprechend den gewünschten Anstrahlwinkeln (15°-90°) verändert werden kann (vgl. Abb. 8). Alle versuchswichtigen Grössen sind genau festgelegt.

Als Messgrösse für den Verschleissbetrag dient entweder das auf einen Vergleichswerkstoff (C 60 N oder C 60 H, in Sonderfällen andere, dem Probenwerkstoff jeweils angepasste Werkstoffe) bezogene *volumetrische* Verschleissbetrags-Verhältnis oder das *lineare* Verschleissbetrags-Verhältnis.

Das Prüfverfahren für Strahlverschleiss soll die Auswahl von Werkstoffen für Teile, die einem Strahl-Verschleiss durch Mineralien unterliegen, erleichtern.

IV. Beratungsgegenstand 50 340 (Schleisschärfe von Mineralien)

Unter „Schleisschärfe" eines Minerals sei (vorläufig) verstanden der Grad der Fähigkeit dieses Minerals, unter speziellen Verschleissbedingungen schleissend zu wirken. Offenbar gibt es keine „absolute", sondern nur eine „spezielle" Schleisschärfe.

Die zahlenmässige Ermittlung der Schleisschärfe erscheint zunächst wichtig für die Durchführung zahlreicher Verschleissprüf-Methoden, bei denen körnige oder stückige Mineralien oder Schleifpapiere verwendet werden. Die grösste Bedeutung aber hat eine exakte Schleisschärfe-Messung für verschiedene „Verschleiss-Industrien." Die Haltbarkeit von Brecherbacken in der Hartzerkleinerung kann z.B. je nach der Schleisschärfe des gebrochenen Minerals zwischen 14 Tagen und 14 Jahren, also im Verhältnis 1:300 und mehr schwanken. Ähnlich starke Einflüsse der Schleisschärfe des Minerals auf den Verschleissbetrag kennt man auch von der Prallmühle und der Schlägermühle her, aus der Rohrmühle, vom Gesteinsbohren und aus der Abraumförderung. Es ist bei dieser enormen (internationalen) praktischen Bedeutung des Problems eigentlich erstaunlich, dass der zahlenmässigen Ermittlung der Schleisschärfe von Mineralien bisher nur verhältnismässig wenige und meist nur spezielle Untersuchungen gewidmet wurden.

Die Beratungen über vorstehenden Gegenstand sind noch in vollem Fluss. Auf diesem Gebiete, wie auch auf den meisten vorgenannten, handelt es sich nicht um die einfache Normung mehr oder weniger abgeschlossener Entwicklungsarbeiten bzw. Forschungsergebnisse, sondern zunächst um die Gewinnung der grundsätzlichen Erkenntnisse. Bisher scheint festzustehen:

(1) Die Schleisschärfe ist keine Konstante für alle denkbaren Verschleissarten. Sie ist vielmehr bestimmt
   (a) durch *innere* Umstände, wie stoffliche Zusammensetzung des Minerals, insbesondere Anteil an „härteren" Bestandteilen, Korngrösse, Bindung usw.

(b) durch *äussere* Umstände, wie Grundkörper (Testwerkstoff) Bewegungsverhältnisse, Anpressung usw.

(2) Daher kann man aus irgendwelchen inneren Eigenschaften des Minerals allein (Härte, Druckfestigkeit usw.) *keine* zuverlässigen Schleisschärfezahlen ableiten.

(3) Die Schleisschärfe eines Minerals kann vielmehr nur für ganz bestimmte und spezielle Verschleissbedingungen angegeben werden; ein spezieller Schleisschärfewert kann nicht ohne weiteres auf andere Verschleissbedingungen übertragen werden.

(4) Daraus folgt, dass, streng genommen, jeder Betriebsfall, bei dem Mineralien schleissend mitwirken, genau imitiert werden müsste, um zu einer zuverlässigen Schleisschärfemessung zu gelangen. Vielleicht kann man einen Mittelweg beschreiten, indem die Schleisschärfebestimmung auf eine Anzahl von 6-8 grundsätzlichen Wirkungsformen von Mineralien beschränkt und entsprechende Prüfeinrichtungen und Prüfmethoden geschaffen werden; dabei können einige der vorgenannten *Verschleiss*-Prüfeinrichtungen vielleicht mit veränderter Zielsetzung als *Schleisschärfe*-Prüfeinrichtungen übernommen werden. Dieser Verhandlungsgegenstand bedarf weiterer Bearbeitung.

V. Beratungsgegenstand 50 341 (Auswahl verschleissfester Werkstoffe)

Wahrscheinlich ist in 80% aller praktischen Fälle die Auswahl geeigneter Werkstoffe für Verschleissteile das geeignetste Mittel zur Verminderung des Verschleisses und der Verschleisskosten. Indes fehlt es z. Zt. an einer guten *Übersicht* über die in Frage kommenden Werkstoffe insgesamt und an klaren Empfehlungen für die Auswahl optimaler Werkstoffe im speziellen Beanspruchungsfall. Dadurch entstehen manche Missgriffe in der Werkstoffauswahl mit entsprechenden Folgen. Es ist das Ziel, durch Weiterbehandlung des Beratungsgegenstandes 50 341 zur Schliessung dieser Lücke beizutragen.

Die noch im Gange befindlichen Arbeiten beschränken sich bewusst auf Fälle von Verschleiss unter Mitwirkung von Mineralien und auf dementsprechende Werkstoffe. Es ist daran gedacht, zunächst allgemeine Gesichtspunkte für die Auswahl solcher Werkstoffe festzulegen. Sodann soll eine Übersicht aller wichtigeren Werkstoffgruppen gegeben werden. Es soll folgen eine Übersicht der hauptsächlichen Beanspruchungsarten, d.h. Wirkungsformen von Mineralien beim Verschleiss praktisch häufiger vorkommender Teile. Abschluss und Hauptteil sollen möglichst konkrete Darlegungen zu der Kardinalfrage bilden: Welche Werkstoffgruppen sollen für welche Beanspruchungsarten bevorzugt werden?

Es wird beim heutigen Stand unserer Erkenntnisse auf dem Verschleissgebiet nicht immer möglich sein, in vorstehend skizzierter Übersicht bis zur Beschreibung des *einzelnen* Werkstoffes vorzudringen. Aber auch schon eine gute *Übersicht* der in Frage kommenden Werkstoffgruppen und -Untergruppen wäre von grossem Nutzen. Die heutige Bearbeitung der Gebiete Festigkeit oder Korrosion wäre ohne derartige Werkstoffübersichten und Anwendungsübersichten völlig unmöglich. Allerdings werden die Schwierigkeiten, die einer Übertragung solcher bewährten Arbeitsmethoden auf das Verschleissgebiet entgegenstehen, keineswegs verkannt.

D. SCHLUSSBEMERKUNG

Vorstehend sollte lediglich ein gedrängter Überblick über verschiedene, teils abgeschlossene, teils laufende Arbeiten eines deutschen Arbeitsausschusses zur Vereinheitlichung auf dem Verschleissgebiet gegeben werden. Dieser Arbeitsausschuss glaubt nicht, auf allen bearbeiteten Teilgebieten bereits die optimalen Lösungen gefunden zu haben. Deshalb ist jede Kritik und jede Anregung zur Verbesserung willkommen.

Da andererseits die Verschleissfrage ein internationales Problem darstellt, von dem alle Industriestaaten der Welt betroffen sind, wünscht der genannte Arbeitsausschuss den lebendigen Kontakt mit Fachleuten anderer Länder, die sich für ähnliche Fragestellungen interessieren. Die neue Zeitschrift „WEAR" scheint in besonderem Masse berufen, den internationalen Gedankenaustausch über Verschleissfragen zu fördern; möge sie ihre Spalten auch weiterhin den Bestrebungen offen halten, auf dem Verschleissgebiet allmählich zu einer besseren Ordnung und internationalen Übereinstimmung zu gelangen.

Eingegangen am 11. Juni, 1957

STANDARDIZATION IN THE FIELD OF WEAR?*

H. WAHL**

Stuttgart (Germany)

A. GENERAL

Standardization is mostly taken up as the final phase of a technical development. Contrary to this, the work of a German group on problems of wear is concerned with a field where neither definitions nor systematics are at hand. Although more than 20,000 papers refer to wear, very few laws or even rules are known to be valid for wear *in toto*. It is hardly possible to give a clear quantitative definition of a case of wear that will distinguish it from another case.

Nevertheless, there are two essential arguments for a limited amount of standardization in the field of wear:

(1) First of all, it will be necessary to make a systematic survey of present-day scattered knowledge on specialized topics. Such classification is actually the essence of work on standards. If done successfully it might well prove to increase the efficiency of future experimental work on wear.

(2) In certain types of wear problems empirical laws become evident. This is the case for example in the wear of metal parts by minerals, which is of eminent practical importance for a diversified number of industries such as mining, ceramics, rock, stone, brick, concrete, and in general all milling operations with hard materials.

The standardization of testing methods in order to determine the wear resistance of materials as well as the abrasiveness (Schleifschärfe) of minerals is obviously the acute problem in these industries.

These motives induced the above-mentioned task group to study some problems of general systematics and also the specialized testing methods for the evaluation of materials resistant to wear by minerals.

This work, which has been going on for a number of years is reviewed here; details are to be found in Standard Specifications***, part of which will be published at a later date.

B. STANDARDIZATION WORK ON THE GENERAL PROBLEM OF ORDER IN THE FIELD OF WEAR

1. DIN Tentative Standard 50 320

Definition of the concept "wear", analysis of wear processes, classification of the field of wear.

* Translated from the original article and condensed by the Editor.

** Chairman of the Working Committee D 4 b for wear problems, a task group of the Materials-testing Standard Committee of the German Standards Organization.

*** Purchasable from Beuth Vertrieb G.m.b.H., Köln.

(a) *Definition of wear:*

The technical term "wear" means the undesirable change of the surface of practical objects owing to the separation of small particles as a consequence of mechanical causes.

(b) *The analysis of wear processes:*

Wear processes in general depend on the following 5 "elements" (Fig. 1):
(i) body (ii) counter-body (iii) intermediary material (iv) motion (v) normal pressure.
A specific wear process is given by a detailed description of these 5 "elements", which also determine the course of the process and the final state.

(c) *Classification of the field of wear in types of wear:*

A type of wear is given by a specific combination of the above 5 "elements". Tables I-III of Fig. 2 give a system of abbreviations for such types of wear.

II. Standard-concept DIN 50 321 (Variables for the amount of wear)

It is suggested that a distinction should be made between "wear" processes and the "amount of wear" as measurable data describing the change of shape of a wearing body.
In order to achieve greater uniformity and comparable standards, a system of variables is given (Fig. 3) and fields of preferred application for certain standards are indicated (Fig. 4).

III. Instructions for wear testing

Discussions are going on concerning the setting up of service testing as well as of laboratory testing.

IV. Concepts

In order to stimulate the uniform use of well-known technical terms, attempts are made to give definitions for a number of general and of specialized (German) terms used in wear technology.

C. STANDARDIZATION WORK ON THE SPECIAL PROBLEM OF THE WEAR OF METALS UNDER THE INFLUENCE OF MINERALS

I. DIN Tentative Standard 50 330 (testing of metals with an abrasive disk)

Conditions of the experiment (see Fig. 5) and of the interpretation of data are standardized; the abrasiveness (Schleifschärfe) of the carborundum paper is tested against a standard steel (C 60 N).
The abrasive disk test seems applicable for the testing of metals in mineral-metal sliding abrasion, up to a normal pressure of 5 kg/cm². This corresponds to service conditions in excavation and hauling operation equipment. Reproducibility is good ($\pm$ 5%) and differentiation between highest and lowest quality about 1:50; good agreement with service life has been established for a number of cases.

II. Abrasive pan testing

Testing with unbound mineral particles is performed in a pan filled with mineral grains or powder, which can be used either dry or with the admixture of water. Fig. 6 gives one of several tentative designs. An attempt is made to achieve unification of testing methods and of evaluation of results.
This test seems suitable for reproduction of service conditions with granulated materials sliding under a low normal pressure.

III. DIN Tentative Standard 50 332 (Jet abrasion test)

This test has been designed to assist in the choice of materials resistant to the abrasive action of jets of mineral particles.
It has been firmly established at the Technische Hochschule, Stuttgart, that abrasive wear under these conditions depends essentially on the true angle of contact. The order of wear resistance in a series of materials changes completely with this angle. It is suggested therefore that the variable angle of contact should be used in testing and results should be plotted as a function of this angle, (see Fig. 7).
Tentative tests are performed with a standardized sandblower of variable blast angle (see Fig. 8). Standard quartz sand is used to compare the performance of materials, while a standard steel (mostly C 60 N or C 60 H) serves to measure the abrasiveness of various granulated materials.

IV. Abrasiveness of minerals

The wear of machine parts in size reduction operations can vary between an average life of a fortnight and 14 years for the same part, depending only on the abrasiveness of the mineral.

Discussions have lead to the conclusion that the abrasiveness of a mineral is *not* an intrinsic property of the mineral but depends on external conditions (discussed already in B I).

The abrasiveness of minerals under service conditions can only be found from tests reproducing accurately the practical case. It is hoped, however, that a limited number of testing machines and standardized tests will ultimately allow a distinction to be made between a few principle types of mineral wear. The aim of this work is to use wear-testing equipment for the evaluation of abrasiveness of minerals.

V. Selection of wear-resistant materials

Work is in progress to formulate some general rules for the selection of materials resistant to abrasive (mineral) wear. Systematics of the types of materials and the types of abrasivity of minerals are in preparation. The final aim is to match abrasion-resistant materials with service conditions.

D. CONCLUSION

The purpose of this survey is to indicate the various activities of this German task group, which aims at greater uniformity in the field of wear.

Criticism and suggestions for improvement are invited.

Since the problem of wear is an international one the German group would welcome contact with specialists in other countries.

Obviously this Journal offers a suitable forum for future discussions.

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GLEIT-, SPÜL- UND STRAHLVERSCHLEISS-PRÜFUNG

K. WELLINGER UND H. UETZ

Staatliche Materialprüfungsanstalt an der Technischen Hochschule, Stuttgart (Deutschland)

ZUSAMMENFASSUNG

Zunächst wird auf die Verschleißprüfung allgemein und dann im besonderen auf Ergebnisse von Gleit-, Spül- und Strahlverschleißprüfungen unter der Wirkung von körnigen Stoffen eingegangen. Die daraus bei den verschiedenen Einflußgrößen wie Härte und Gefüge der Werkstoffe, Härte der verschleißwirkenden Stoffe, Befeuchtung, Temperatur, Anstrahlwinkel u.a.m. gewonnenen grundsätzlichen Erkenntnisse über des Verschleißverhalten verschiedenartiger Werkstoffe wie Stähle, Hartguß, Schmelzbasalt, Sinterkorund, Gummi u.a. werden dargelegt und Hinweise für die Bearbeitung von Verschleißfragen gegeben.

SUMMARY

After some introductory remarks on wear-testing in general the author discusses the abrasive effects of granulated materials under conditions of dry or wet sliding, "rinsing" with a suspension or a sludge of granulated materials, and blasting. The experience gained with reference to such variables as the hardness and structure of abraded material, the hardness of the abrasive, the influence of moisture and temperature as well as that of the angle of the abrasive beam in blasting tests, is reported. The abrasive resistance of various materials, *e.g.* steel, white cast iron, smelt-basalt, sintered corundum, and rubber, is considered in the light of this knowledge and some directions are given for the study of wear problems.

Die in der Staatlichen Materialprüfungsanstalt Stuttgart auf dem Gebiet der Verschleißprüfung allgemein und in Untersuchungen auf dem Gebiet des Gleit-, Spül- und Strahlverschleißes unter der Wirkung von körnigen Stoffen gewonnenen wesentlichen Erkenntnisse über das Verschleißverhalten verschiedenartiger Werkstoffe sind im folgenden zusammengestellt.

Allgemein wird der Verschleiß eines Bauteiles von den Betriebsbedingungen, von seiner Form und von dem verwendeten Werkstoff beeinflußt. Da Betriebsbedingungen und Form meist nur wenig verändert werden können, wird angestrebt, den Verschleiß durch Verwendung eines geeigneten Werkstoffes möglichst niedrig zu halten. Die richtige Wahl des Werkstoffes ist jedoch schwierig, weil über grundsätzliche Verschleißeigenschaften der Werkstoffe wenig bekannt ist, noch weniger über das Verschleißverhalten unter bestimmten Betriebsbedingungen.

Die in Betracht kommenden Werkstoffe müssen deshalb zunächst im *Betriebsverschleißversuch* geprüft werden, auch wenn dies u.U. mit erheblichem Zeit- und Kostenaufwand verbunden ist. Die Prüfung im *Modell-Verschleiß-Versuch* und

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insbesondere die Prüfung in *Verschleiß-Prüfmaschinen* bieten die Möglichkeit, mit erträglichem Zeit- und Kostenaufwand bei den verschiedenen Verschleißarten einzelne Einflüsse systematisch zu ändern und damit grundsätzliche Erkenntnisse über das Verschleißverhalten der Werkstoffe zu erhalten.

Zur Nachprüfung, inwieweit die gewählten Bedingungen denen im Betrieb entsprechen, sind Vergleichsversuche mit sich im Verschleißverhalten wesentlich unterscheidenden Werkstoffen zweckmäßig. Besteht keine Übereinstimmung zwischen den Ergebnissen von Betriebs- und den Laboratoriumsversuchen, dann müssen die Versuchsbedingungen den Betriebsbedingungen mehr und mehr angepaßt werden, bis Übereinstimmung erreicht ist. Oft ist hierzu die Entwicklung einer besonderen Verschleißeinrichtung erforderlich.

In Gleit-, Spül- und Strahlverschleißversuchen wurden verschiedenartige Werkstoffe — mehrere Stahlsorten, Hartguß, Hartmetalle, Schmelzbasalt, Sinterkorund und gummiartige Stoffe — auf ihr Verschleißverhalten gegen körnige Gegenstoffe — Kalk, Berge, Glas, Koksgrus, Flint, Flußsande, Quarz, Korund, Siliziumkarbid und verschieden harte Gußschrote — untersucht. Die verwendeten Versuchseinrichtungen bzw. -verfahren, d.s. Verschleißtopf, Schleifpapierverfahren und Sandstrahlgebläse, gestatten, den Gleit-, den Spül- und den Strahlverschleiß jeweils in bezug auf verschiedene Einflußgrößen zu untersuchen.

Beim Strahlverschleiß ist die Größe des Verschleißes in starkem Maße vom Anstrahlwinkel abhängig; die Bewährungsfolge der Werkstoffe ist je nach Größe des Anstrahlwinkels verschieden. Dies geht aus Abb. 1 hervor, in dem der Verschleiß von C 60 H, Hartguß, Schmelzbasalt und Gummi bezogen auf den von St 37 in Abhängigkeit vom Anstrahlwinkel dargestellt ist. Für St 37 sind die absoluten Verschleißwerte in μ/h eingetragen.

Bei der Bearbeitung praktischer Verschleißprobleme muß der auftretende Anstrahlwinkel berücksichtigt werden. Dabei ist jedoch zu beachten, daß der Winkel sich infolge des auftretenden Verschleißes u.U. örtlich ändert (Muldenbildung).

Die Höhe des Verschleißes, das Bewährungsverhältnis und die Bewährungsfolge der Werkstoffe werden auch vom verschleißwirkenden Stoff beeinflußt. In der Regel ist bei einem Werkstoff, der härter ist als der verschleißwirkende Stoff, niedriger Verschleiß („Tieflage") und bei einem Werkstoff, der weicher ist als der verschleißwirkende Stoff, hoher Verschleiß („Hochlage") zu erwarten. Beispiele hierfür zeigen Abb. 2 bis 4 für Gleitverschleiß, für Spülverschleiß und für Prallstrahlverschleiß. Der Verschleiß von verschiedenen Werkstoffen ist jeweils in Abhängigkeit von der Härte des verschleißwirkenden Stoffes aufgetragen. In dem zwischen „Tief- und Hochlage" liegenden Gebiet des „Steilanstieges" verursachen schon verhältnismäßig kleine Unterschiede in der Kornhärte große Änderungen des Verschleißes und der Bewährungsverhältnisse der Werkstoffe. Die praktischen Fälle befinden sich meist im Gebiet des „Steilanstieges"; deshalb ist die Kenntnis der verschleissenden Wirkung von körnigen Stoffen, d.h. die „Schleißschärfe" von großer Bedeutung.

Für die Bewährungsfolge gleichartiger Werkstoffe wie ferritisch-perlitische Werkstoffe, perlitisch-martensitische Werkstoffe, Werkstoffe mit Karbiden, nichtmetalli-

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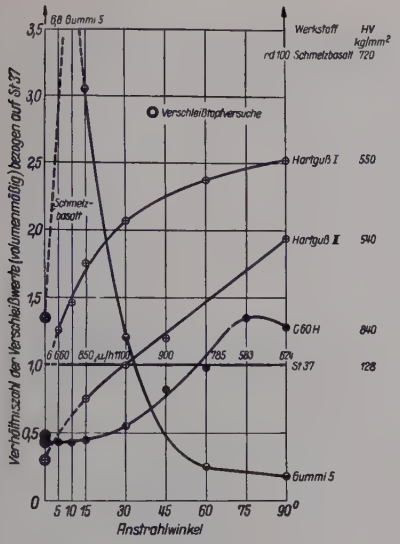

Abb. 1. Strahlverschleiß-Anstrahlwinkel-Schaubild. Einfluß des Anstrahlwinkels bei verschiedenen Werkstoffen. Sandstrahlgebläse; Blasgut: Quarzsand, Körnung $>0.2 \leq 1.5$ mm; Blasdruck 1 atü.
Verhältniszahlen bei Anstrahlwinkel 0° aus Gleitverschleißversuchen mit dem Verschleißtopf.

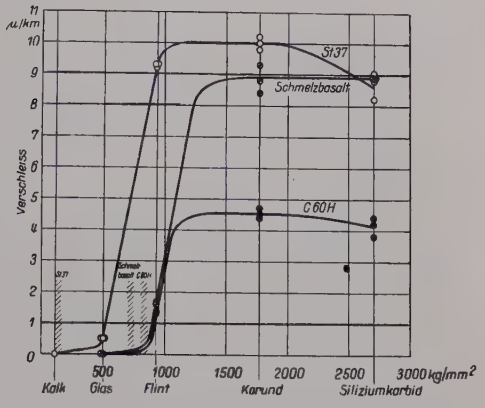

Abb. 2. Einfluß der Kornhärte des verschleißwirkenden Stoffes (trocken) auf den Gleitverschleiß von Stahl St 37 und Stahl C 60 H, sowie Schmelzbasalt.
Verschleißtopf. Kalk Körnung 0.2 bis 3 mm, übrige verschleißwirkende Stoffe Körnung 30, Gleitgeschwindigkeit 1.85 m/sec. Die Härtebereiche der Werkstoffe sind eingezeichnet.

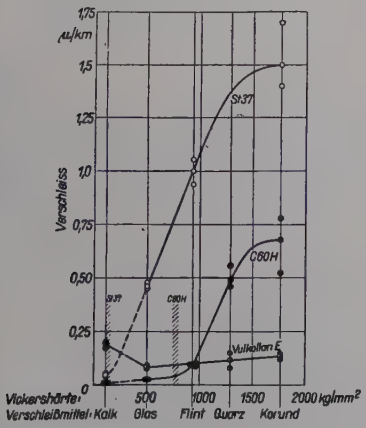

Abb. 3. Einfluß der Kornhärte des Spülgutes auf den Verschleiß von Stahl St 37 (HV = 110 kg/mm²) und C 60 H (HV 10 = 750 kg/mm²) sowie Vulkollan.
Volum-Mischungsverhältnis Wasser/Spülgut = 1:1, Körnung 30, Gleitgeschwindigkeit 6.4 m/sec. Die Härtebereiche der Stähle sind eingezeichnet.

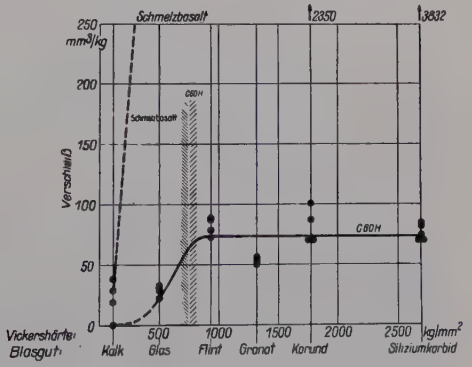

Abb. 4. Abhängigkeit des Prallstrahlverschleißes von der Härte des Blasgutes für C 60 H und Schmelzbasalt.
Sandstrahlgebläse. Korngröße: Kalk $>0.2 \leq 3$ mm; übrige Blasgüter Körnung 30. Blasdruck 1 atü. Die Härtebereiche der Werkstoffe sind eingezeichnet.

sche Werkstoffe (Schmelzbasalt, Quarzglas und Sinterkorund) und Grauguß ist bei Gleitbeanspruchung im allgemeinen die Härte des Werkstoffes maßgebend, Abb. 5. Dies gilt in der Regel auch für den Strahlverschleiß im Prallstrahlgebiet, sofern die Härte des Blasgutes kleiner ist als die Härte des Werkstoffes; ist jedoch die Härte des Blasgutes größer als die Werkstoffhärte, dann sind die weicheren Werkstoffe im allgemeinen günstiger als die härteren, Abb. 6 und 1.

Einflüsse wie Geschwindigkeit, Temperatur, Korrosion können u.U. so groß sein, daß sie die obengenannten überwiegen und für das Verschleißverhalten ausschlaggebend sind.

Den Einfluß der Geschwindigkeit bei Prallstrahlverschleiß zeigt Abb. 7. Der Verschleiß von C 60 H ist im Bereich der Geschwindigkeit von 35 m/sec mit Quarzsand praktisch gleich dem von St 37. Mit zunehmender Geschwindigkeit wird der Verschleiß von C 60 H größer, mit abnehmender Geschwindigkeit kleiner als der von St 37. Das bei niedrigen Geschwindigkeiten so günstige Verhalten von Gummi bei senkrechter Anstrahlung wird mit zunehmender Geschwindigkeit im Vergleich zu den Stählen ungünstiger. Der Verschleiß von Schmelzbasalt liegt im Vergleich zu den Stählen ungefähr zwei Größenordnungen höher.

Während des Verschleißvorganges wirkende bzw. entstehende Wärme kann den Verschleiß in beträchtlichem Maße beienflussen. Dies zeigen die in Abb. 8 dargestellten Ergebnisse. Bei den gewählten Versuchsbedingungen fällt bei St 35 der Verschleiß mit zunehmender Temperatur zunächst ab und steigt dann an, bei C 60 H nimmt er mehr und mehr zu. Bei Sinterkorund wird der Verschleiß mit zunehmender Temperatur immer kleiner.

Die Ursache des zunächst mit zunehmender Temperatur abfallenden Verschleißes von St 35 dürfte auf eine sich bildende Oxydschicht zurückzuführen sein, deren Mikrohärten zwischen 200 und 900 kg/mm² liegen. Der größere Verschleiß von C 60 H gegenüber St 35 bei höheren Temperaturen ist vermutlich auf eine unterschiedliche Ausbildung dieser Oxyd-Schicht zurückzuführen.

Bei Strahlverschleißbeanspruchung hat die Temperatur bei den Eisenwerkstoffen einen geringeren Einfluß, Abb. 9. Eine große Abhängigkeit zeigt der Sinterkorund, mit zunehmender Temperatur verhält er sich insbesondere bei Prallstrahlbeanspruchung wesentlich günstiger.

Der Einfluß der Befeuchtung bei Gleitverschleißbeanspruchung ist von großer Bedeutung, Abb. 10.

Die Stähle St 37 und C 60 H haben ein mehr oder weniger ausgeprägtes Verschleißmaximum im Bereich geringer Befeuchtung. Die gummiartigen Werkstoffe mit ihrem hohen Verschleiß bei trockener Gleitbeanspruchung verhalten sich bei Befeuchtung sehr günstig; so hat Vulkollan bei Mischungsverhältnissen über 0.1 unter den angewandten Bedingungen niedrigeren Verschleiß als C 60 H.

Der bei Stahl und den gummiartigen Werkstoffen im Bereich kleiner Befeuchtung unterschiedliche Charakter der Verschleißkurven dürfte im wesentlichen auf die mit der Befeuchtung sich ändernden Reibungs- und Pressungsverhältnisse zurückzuführen sein.

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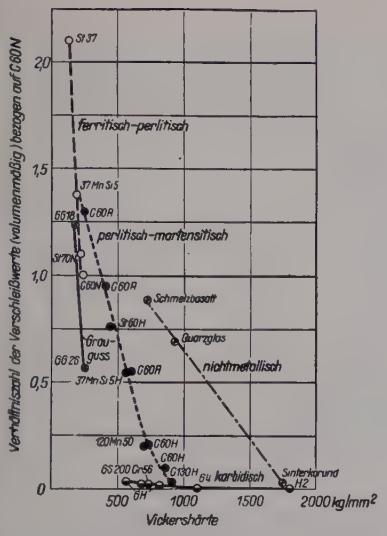

Abb. 5. Abhängigkeit des Verschleißes von Gefüge und Härte der Werkstoffe
ferritisch-perlitische Werkstoffe (lamellarer Zementit)
perlitisch-martensitische Werkstoffe (körniger Zementit)
nichtmetallische Werkstoffe
Werkstoffe mit Karbiden (Hartguß = GH, Sinterhartmetalle = G 4 und H 2)
Grauguß (lamellarer Zementit)
Schleifpapierversuche mit Flint Körnung 80; mittlere Gleitgeschwindigkeit 0.25 m/sec, Flächenpressung 3.9 kg/cm².

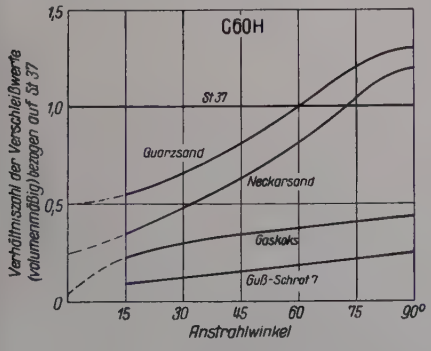

Abb. 6. Strahlverschleiß-Anstrahlwinkel-Schaubild. Einfluß des Blasgutes bei C 60 H (Härte HV = 820 kg/mm²).
Sandstrahlgebläse.
Blasgut:
Quarzsand Korngröße >0.2 ≤ 1.5 mm, HV 1290 kg/mm²
Neckarsand Korngröße ≤ 3 mm
Gaskoks Korngröße ≤ 4 mm, HV = 550 kg/mm²
Gußschrot Korngröße rd. 1.6 mm, HV = 690 bis 750 kg/mm²
Blasdruck 1 atü.

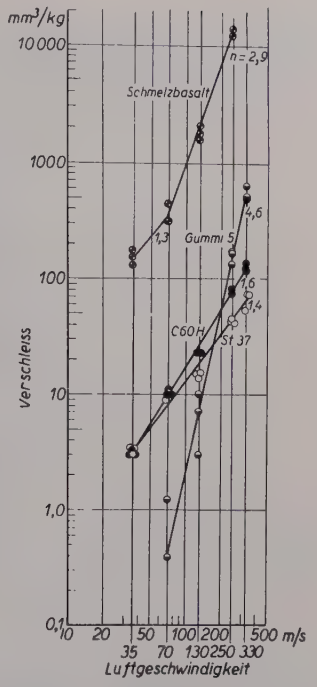

Abb. 7. Abhängigkeit des Prallstrahlverschleißes von der Luftgeschwindigkeit.
Sandstrahlgebläse. Blasgut: Quarzsand, Korngröße >0.2 ≤ 1.5 mm; n Steigung der Kurven.

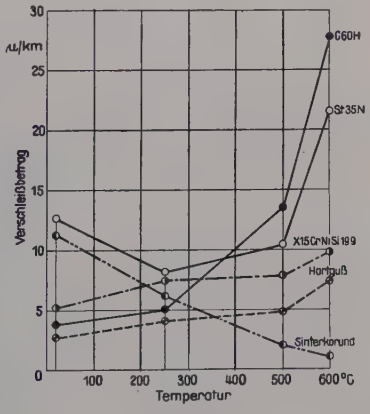

Abb. 8. Abhängigkeit des Gleitverschleißes von der Temperatur. Verschleißtopf; Gleitgeschwindigkeit 2.8 m/sec, Laufweg 2.5 km; verschleißwirkender Stoff. Korund, Korngröße 3-5 mm.

Bei gleichzeitigem Angriff durch Verschleiß und Korrosion wirkt sich die Korrosion bei den verschiedenartigen Werkstoffen unterschiedlich aus. Dies zeigen die in Abb. 11 dargestellten Ergebnisse. Unter den gewählten Bedingungen kommt die Korrosion

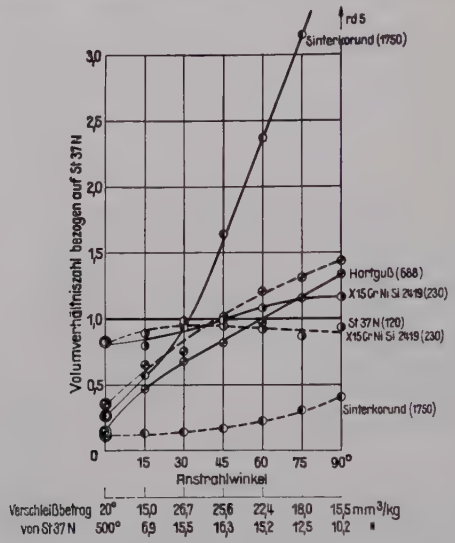

Abb. 9. Strahlverschleiß-Anstrahlwinkel-Schaubild für 20°C (——) und 500°C (- - - -) Versuchstemperatur. Sandstrahlgebläse. Blasgut: Neckarsand, Korngröße < 3 mm, Blasdruck 0.5 atü.
Verhältniszahlen bei Anstrahlwinkel 0° aus Gleitverschleißversuchen mit dem Verschleißtopf. Werte in Klammer bedeuten die Vickershärte.

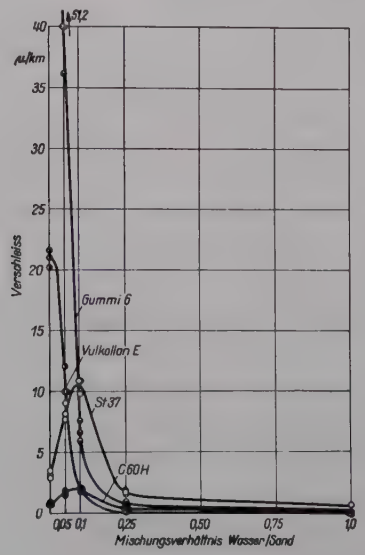

Abb. 10. Einfluß der Befeuchtung auf den Gleitverschleiß.
Verschleißtopf; verschleißwirkender Stoff: Neckarsand, Korngröße < 3 mm. Die Verschleißwerte beim Mischungsverhältnis null entsprechen den mit trockenem Sand erhaltenen Ergebnissen. Gleitgeschwindigkeit 2.5 m/sec beim Mischungsverhältnis 0 bis 0.25 bzw. 5 m/sec beim Mischungsverhältnis 1.

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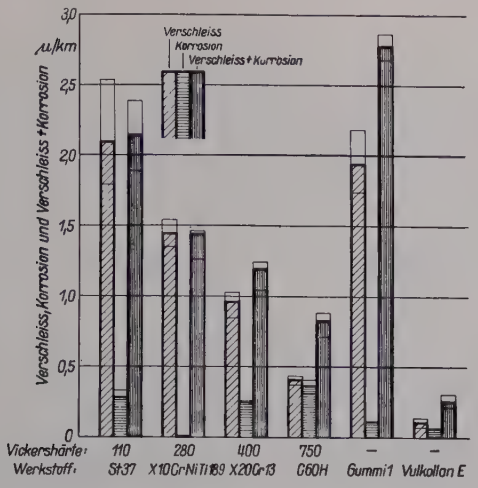

Abb. 11. Gegenüberstellung der Ergebnisse von Verschleiß-, Korrosions- sowie Verschleiß *und* Korrosionsversuchen.
Spülverschleißverfahren; verschleißwirkender Stoff: Quarzsand, Korngröße $>0.2 \leq 1.5$ mm, Korrosionsmittel 1%ige Schwefelsäure, Mischungsverhältnis Flüssigkeit/Spülgut = 1:1, Gleitgeschwindigkeit 6.4 m/sec.

bei St 37 infolge des verhältnismäßig hohen Verschleißes praktisch nicht zur Auswirkung. Beim korrosionsbeständigen Stahl X 10 CrNiTi 18 9 ist erwartungsgemäß nur der Verschleiß maßgebend. Beim 13%igen Chromstahl und beim C 60 H ergibt sich eine Summierung von Verschleiß und Korrosion. Dagegen wird bei Gummi und Vulkollan der Verschleiß durch die Korrosion begünstigt.

LITERATUR

Zusammenstellung der Mitteilungen aus der Staatlichen Materialprüfungsanstalt über Untersuchungen auf dem Gebiet des Gleit-, Spül- und Strahlverschleißes unter der Wirkung von körnigen Stoffen

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Eingegangen am 29. August, 1957

ALLEVIATING ABRASIVE WEAR IN CERAMIC INDUSTRY HANDLING EQUIPMENT

C. M. ALLEN

Battelle Memorial Institute, Columbus, Ohio (U.S.A.)

SUMMARY

Abrasive wear of equipment and parts which come in contact with raw materials in ceramic forming and fabricating processes is, at present, costly. Though the result of wear is easily understood, the processes and causes of abrasive wear are rather complex and not always fully appreciated. It is the purpose here to point out the problems associated with abrasive wear of ceramic equipment components, discuss what developments have been made in alleviating abrasive wear, and to suggest that the manufacturers of ceramic products for insulator, refractory, building, and ornamental use give serious consideration to the many new technological advances in materials for alleviating wear problems in ceramic plant equipment.

Abrasive wear can often be reduced by giving careful consideration to the environmental conditions — humidity, abrasiveness of material being handled, frictional energy expended, and resultant surface temperatures — and then selecting materials which have the proper combination of hardness, toughness and resilience, resistance to corrosion, and cost.

The hardest material may not always be the best material for alleviating abrasive wear. For example, in a corrosive environment, the use of a more corrosion resistant alloy, though softer than a less corrosion resistant material, may offer advantages in certain applications through extended life and reduced maintenance costs. It is suggested that abrasive wear may also be alleviated by the judicious use of hard surfacing materials applied by welding, brazing, plating, certain diffusion processes, and flame spraying of ceramics and cermets. It might be well for plant management to review maintenance records periodically to see where costs attributable to wear can be profitably decreased. An effective way of embarking on a wear-combatant plant program is to consult with specialists in the field of abrasive wear.

RÉSUMÉ

De nos jours, l'usure créée par le contact avec les matières premières dans les équipements et les pièces utilisées au cours du modelage et de la fabrication de la céramique, revient chère. Les effets de cette usure sont bien connus; il en va tout autrement des causes et des progrès de la déterioration elle-même, phénomènes complexes et assez mal compris.

On souligne ici les problèmes posés par l'usure des pièces d'équipement utilisées dans les fabriques de céramique, ainsi que les mesures prises contre elle et on suggère aux fabricants de produits céramiques isolants, réfractaires, de construction ou d'ornementation, de bien vouloir considérer avec soin les progrès techniques réalisés dans la production de matériaux permettant un allegèment de ce problème propre à l'équipement de leurs fabriques.

Que l'on considère d'abord le milieu et ses conditions: l'humidité, l'abrasivité du matériel traité, l'énergie de friction accrue et les températures de surface qui en résultent. Que l'on choisisse les matériaux où soient le plus heureusement combinés la dureté, la solidité, la résistance à la corrosion, sans oublier le prix.

Le matériel le plus dur n'est pas toujours le meilleur contre l'usure. Dans un milieu corrosif par exemple, il est possible qu'un alliage offrant une meilleure resistance à la corrosion, bien que plus mou qu'un autre moins résistant, offre, dans certaines applications, de plus grands avantages grâce à une durée de vie prolongée et à une réduction des frais d'entretien.

Que l'on fasse un choix judicieux des matériaux de revêtement appliqués aux produits céramiques et aux cermets par les procédés de soudure, brasure, électrolyse ou autres, ou par certaines méthodes de diffusion ou pulvérisation à la flamme. Que la direction des fabriques procède à un examen périodique des dossiers concernant l'entretien, afin de déterminer les endroits où les frais dûs à l'usure pourraient être diminués avec profit.

Enfin, si l'on veut envisager avec succes un programme de lutte contre la détérioration par la friction à la fabrique, que l'on n'hésite pas à consulter les spécialistes dans le domaine de l'usure.

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INTRODUCTION

Because the wear of equipment used to handle and form ceramic products costs millions of dollars a year, it should be of primary concern to the ceramic industry. The costs of the material and labor to make replacement parts and of the labor to install them, as well as the loss of production during shutdowns, account for the bulk of the expense. A hidden cost that also results from wear of machinery is the loss of efficiency. When efficiency suddenly drops, as when breakage of a part occurs, industry takes immediate action. Ordinarily, industry does not investigate a gradual decrease in efficiency, which may have its origin in gradual wear. Ceramic-plant operating personnel are generally unaware of the substantial savings that can be effected by the application of superior wear-resistant materials to high-maintenance parts.

Wear is a rather complex phenomenon, and no generalized solution to wear problems can be found. Each industry, and sometimes each machine or part, has wear problems which, in themselves, are unique. A satisfactory solution to a wear problem in one piece of equipment does not mean that the same solution can or should be used in another.

The abrasive wear process

Perhaps a brief discussion of the abrasive wear process will lead to a better understanding of why wear is such a serious and expensive problem. Generally speaking, wear can come about by abrasion, corrosion, battering and by fatigue or breakage. Abrasive wear is generally a gradual process and is regarded as a surface phenomenon resulting from the scratching and scoring of a solid surface in contact with loose particles of a solid, or from the scoring of two solid surfaces when an abrasive material is present between them[1]. Corrosive wear is closely allied with abrasive wear in that the corrosion products are usually abrasive in themselves and produce accelerated wear. Battering is usually associated with impact loading in which a part is subjected to stresses in excess of the yield strength of the material from which the part is made. Wear resulting from fatigue or breakage can be a secondary effect of abrasive wear, where the part is weakened until a gross (as contrasted with gradual) failure occurs. Wear, then, may be simply described as the undesired change in dimensions of a part which is subjected to friction, corrosion, stress, or combinations of these, in service. There is nothing complicated about this. However, the reasons why one material wears rapidly and another resists wear quite well are not always so easily understood or appreciated.

Normally, because the loose particles of many solids are quite hard, they cut and abrade the surfaces with which they come into contact. Thus, the surface of a part which must resist abrasive wear should be hard. In alloys, it is the hard particles, usually iron carbide in ferrous base alloys, which provide the hardness. To resist wear, the carbide particles must be supported and bonded with as tough a matrix material as possible. However, when the matrix material is too soft, it may be abraded preferentially in service, thereby placing the carbides in relief; their support and bond is

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weakened until they are torn loose by the rubbing friction. Of course, there are exceptions, for it is not always necessary to have hard materials to resist abrasion. Tough and resilient materials, such as rubber, resist wear very well in some applications.

Closely related to resistance to abrasive wear is resistance to corrosion. In selecting a material for a particular application, it is necessary to know and understand what effect the environmental conditions are likely to have on the wear process. The process of corrosion often forms protective coatings which inhibit further corrosion. Abrasion can destroy these coatings and allow further corrosion to take place. In this way, abrasive wear can greatly accelerate corrosion. Hence, the selection of materials for resisting abrasive wear in a particular application must be based on considerations of environment, material hardness, toughness and resilience, resistance to corrosion and, of course, cost.

Wear problems in the ceramic industry

There are many varieties of equipment used in the fabrication of finished ceramic products for insulating, refractory, ornamental, and building applications. Generally, the refractory materials are more abrasive than the clay materials used in building bricks and tiles. Crushing the grinding equipment probably present the most serious wear problems. Such parts as crusher jaws, cores, or rolls, Muller tires, pan bottoms, and screen plates are all subjected to severe abrasive wear. The more abrasive the material being handled, the greater the wear. Secondary machine parts such as bearings, guides, and guide blocks also present serious wear problems. The wear of dry press dies is particularly serious since the high pressures used in the forming result in high frictional forces between the mix and the die liner. All of these parts require materials that are especially suited for each individual application.

TABLE I

DESIRED CHARACTERISTICS FOR WEAR RESISTANCE OF SOME CERAMIC EQUIPMENT MACHINERY PARTS

Equipment parts	*Property requirements*		
	Hardness	*Impact resistance*	*Corrosion resistance*
Shovel teeth	High	High	High
Crusher jaws and cones	High	High	High
Crusher jaws and rolls	High	High	Medium
Dry pan, bottoms, screenplate, tires	High	High	Medium
Scrapers, knives, plows	High	Medium	Medium
Pug Mill knives	High	Medium	High
Wet pan bottoms and tires	High	Medium	High
Slip cast mixer knives	High	Low	High
Augers and extrusion die liners	High	High	High
Repress die liners	High	Low	High
Dry press die liners	High	High	Medium

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Table 1 presents a few components of ceramic industry equipment, together with the properties which are believed necessary for good performance. Note that 6 components require a combination of high hardness and impact resistance and 8 components demand high corrosion resistance, while only 3 demand maximum hardness. impact resistance, and corrosion resistance simultaneously.

DEVELOPMENTS FOR REDUCING ABRASIVE WEAR IN CERAMIC MACHINERY

Ferrous materials

Manganese steel is frequently used where considerable abrasion and abuse are involved, such as in shovel teeth. This is a very interesting abrasion-resistant material. Its composition is about 1 per cent carbon, 1/2 per cent silicon, and 12 per cent manganese, with the balance iron. As cast, the metal is brittle; after heat treatment it has good wear resistance, though its hardness is then only about 200 Brinell. With suitable heat treatment, manganese steel will have an austenitic structure. Cold working during use transforms the surface to a hard martensite. As the martensite wears away, more austenite is transformed to martensite, thus replenishing the hard surface layer. Manganese steel is resistant to abrasion because it has high surface hardness and corrosion resistance, combined with an impact-resistant core.

Alloy white cast iron has become quite popular where abrasion resistance is required. The alloying elements, nickel and chromium, are added to strengthen the matrix material. Alloy white iron has approximately twice the life of manganese steel in ball mill liners and has given over twice the life of ordinary chilled iron plates in airless grit-blasting machines. It is somewhat cheaper than manganese steel.

Chromium-iron alloys have been produced with various amounts of chromium. A typical low chromium-iron alloy (1.5% Cr, 4.62% Ni, 3.4% C) can have a hardness of the order of 700 Brinell. It is quite abrasion-resistant but only moderately corrosion-resistant. Chromium-iron alloys containing approximately 28% Cr and 2.5% C can be made to have good abrasion resistance and excellent corrosion resistance. Its hardness, about 460 Brinell, is lower than the low chromium alloy but it is much more impact-resistant. Although it is softer by the Brinell Hardness test, this alloy forms very hard, abrasion-resistant, chromium carbides supported in a matrix of alloyed ferrite which is stronger than the matrix materials in the low-chromium alloy.

The versatility which can be obtained by heat treatment of the high-chromium alloy provides an attraction not generally present in other alloys. Its performance in ceramic equipment in the few places it has been used has been outstanding[2]. High-chromium iron alloys are reported to be superior for die liners and pan bottoms[3]. Die-liner life was increased 100 times as compared with white iron and 25% better life was obtained when the chromium alloy was used for wet pan bottoms in place of white cast iron.

Other advantages of the high chromium iron alloys are their excellent castability

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with very small shrinkage and their good machinability after heat treatment. Subsequent hardening can be accomplished with a minimum of scaling and distortion. The high chromium-iron alloys resist surface softening when subjected to high frictional heat generation in use. This is another important criterion for abrasion-resistant materials. All of these characteristics would appear to make the high-chromium alloys quite useful in ceramic machinery. Unfortunately, these alloys are more expensive than those currently being used and, as a result, have not been very widely used in ceramic plants. However, more complete evaluation of the alloy may result in over-all cost savings.

Hard-facing materials

Coatings of hard materials are frequently applied to tough base materials that will withstand the impact loads of such operations as crushing. Several hard-facing[6] materials are available and they are usually applied as electrodeposits, by welding, either electrically or with an acetylene torch, and by metal spraying techniques[9].

Electrodeposits of chromium have been used in ceramic equipment with varying success[8]. Chromium plating did not lengthen the life of pug mill knives; on the other hand, it is reported that chromium-plated die liners have given exceptionally good life.

One point which is frequently overlooked in hard-facing or chromium-plating parts is that it is very important that the base material be reasonably hard. If it is too soft it will not support the hard surfacing materials and cracking and spalling may occur in use as a result of high unit loading. Spalling may be caused by poor bonding or by brittle fracture, since many of the hard-facing materials have little impact resistance. It is advisable to consult with the producers of the hard-facing alloys before applying them indiscriminately to ceramic-equipment parts. Methods of application and the selection of the proper hard-facing alloy for a given job can best be made by experienced engineers.

Tungsten carbide for special applications

Tungsten carbide has been adapted for use in the ceramic industry. In the past few years, this material has been used for fluid nozzles and spray guns with excellent results. Hammer-mill blades have been tipped with tungsten carbide with very good results. Normally, tungsten carbide is sintered and pieces are applied to a base metal by brazing. Recently, welding rods have been developed which permit the deposition of tungsten carbide particles in a hard matrix. In Great Britain, the material is electric-welded with a composite electrode consisting of a mild steel tube filled with tungsten carbide particles with or without other metals. This deposit has been used successfully on excavator teeth in the refractories industry and on cutter picks. In the United States, a similar development has been made using both tubes and solid rods of tungsten carbide with a cobalt-chromium-iron matrix material. This type of material should prove useful if sufficient life can be obtained to justify its high cost.

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Relatively new materials and methods for alleviating abrasive wear

A wide variety of new materials and methods of resisting abrasive wear have become available in recent years. Those that appear to offer promise for alleviating wear in ceramic equipment are described briefly below.

Diffusion and impregnation treatments: Many surface treatments other than alloying, facing, or brazing, appear to be worthy of consideration. Siliconized and chromized steel offer considerable promise because a part so treated can possess a tough core of a suitable base material and a surface that is resistant to corrosion and abrasion. A steel or cast iron part treated with silicon at high temperature forms a very hard case. Silicon impregnates the surface, forming a silicon-rich solid solution that is resistant to corrosion.

By a diffusion-treatment with chromium a part can be given a very hard and very corrosion-resistant surface[4,7]. Chromium diffuses through the steel or cast iron with very little change in the dimensions of the part. Thus, machining after treatment is usually unnecessary. Aluminumizing is a relatively new treatment which imparts both surface hardness and corrosion resistance to ferrous base materials. One of the simplest methods involves the application of aluminum by dipping the part in molten aluminum. This is followed by a diffusion heat-treatment. Sometimes, a surface layer of aluminum and silicon is painted on the surface — this is then followed by a diffusion heat-treatment. The diffusion process results in the formation of hard aluminum-iron and silicon-iron compounds. This is a relatively inexpensive surface treatment. To insure adequate toughness, it is necessary to restore the temper of the part by proper heat treatment, after diffusion has been completed. Impregnated and diffusion-treated parts should be competitive, economically, with parts now in use.

Ceramic and cermet materials: Hard ceramics should be considered for possible use as spray nozzles and as liners in forming operations. These materials have been proven in the laboratory to be comparable to tungsten carbide in resistance to wear. Dense pressings of aluminum oxide and boron carbide have excellent abrasion resistance and should be useful where high impact resistance is not necessary.

For certain applications the use of ceramic and cermet coatings on suitable base materials may be profitable. Techniques have been developed for flame-spraying aluminum oxide and tungsten carbide on metal surfaces[5]. This process yields a bonded ceramic or cermet coating on metal base materials and should provide excellent abrasion resistance. The process is generally more costly than the diffusion processes mentioned earlier.

CONCLUSIONS

It appears that there are many new, and, as yet, many untried materials and methods for alleviating abrasive wear in ceramic plant equipment. It appears, therefore,

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that ceramics industry management should review seriously the plant costs attributable to wear and consider the possibilities of reducing these costs. In many cases, the judicious selection and applications of new or improved materials could significantly reduce the toll of abrasive wear.

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Received July 22, 1957

PRACTICAL MEASURES TO PREVENT ABNORMAL WEAR IN A STEEL MILL

J. DE VRIES*

Royal Netherlands Blast-furnaces and Steel-works, IJmuiden (The Netherlands)

SUMMARY

In this paper some general rules and practical measures for avoiding abnormal wear are given. Examples of considerable improvement brought about in the application of steel wire ropes, the sealing of pumpshafts, and protection of bearings in dusty surroundings and of tubes, are described.

ZUSAMMENFASSUNG

Massnahmen und Empfehlungen zum Vorbeugen übermässiger Abnutzung. Beispiele bedeutender Verbesserungen in der Lebensdauer von Drahtseilen, Stopfbüchsen von Pumpenachsen, Lager in staubiger Umgebung und Röhren werden erörtert.

INTRODUCTION

The cases presented in this paper are selected from the wide experience of the different sections of K.N.H.S. (Royal Netherlands Blast-furnaces and Steel-works), IJmuiden, The Netherlands, in the field of wear prevention, during the post-war years.

Without exception, all cases mentioned are related to abnormal wear phenomena. Excessive wear is not only expensive but also very troublesome, especially in plants where machines are in continuous operation. To shut down, even for a matter of minutes, means a loss in output of many tons. Normal working conditions in a steel plant are themselves extremely severe, owing to high temperatures, high loads, dusty atmosphere, etc. Under these conditions the weak spots of a construction will show up within a few weeks, while under less severe conditions this would happen only after years or never at all.

Some general rules

(a) All rubbing surfaces that come into contact with sand, ore, scale and other abrasive matter, should be hardened.

(b) Unit loads should be kept as low as possible.

(c) In a dusty atmosphere one should try to avoid the application of reciprocating machine-parts and the like, because an efficient sealing of those bearings against foreign matter is difficult to maintain. If no other solution is possible they must be protected by covers of the "bellows" type. In this case, however, one has to take into consideration the pumping action of such a cover. Sometimes an air-filter element must be provided on the cover.

* Paper read before the Wear Section of the Bond voor Materialenkennis at Utrecht on February 25th, 1955, and published (in Dutch) in *Metalen*, *10* (10) (1955).

(d) There should be large scale application of automatic or centralized lubrication.
(e) The surrounding atmosphere should be purified by means of dust-removing equipment. Because of the high maintenance costs of such installations, this purifying of the air has been restricted up to now to those places where dust is a hindrance to the workers. But we must not forget that in combating excessive wear dust prevention is of primary importance.

Steel wire ropes

In normal wire rope construction, the strands of the different layers are laid at mutual equal angles; this causes unequal pitch of the wires in the different layers. Consequently, the profile of a certain layer of wires does not match the groove of the profile of the foregoing layer; hence the wires cross each other. This means a secondary bending of the wires and extra internal wear. The normal wire rope is composed of wires of equal size.

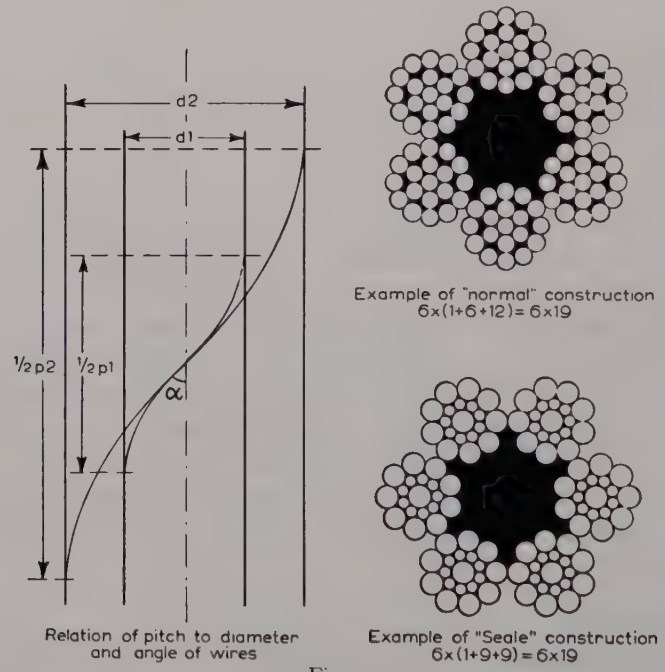

Fig. 1

During the last 25 years, different wire rope constructions have been developed. In the "Seale" construction, the wires of the different layers in the strands are laid at equal pitch instead of at equal angles (see Fig. 1).

In this way the outline profile of a certain layer matches the profile of the foregoing layer over the entire length of the wire rope. The "Seale" construction has the additional advantage that the diameter of the wire of the outside layer is larger than that of the inside layers. This design has no ill effect on the flexibility, provided that the strands consist of more than 19 wires. The outer wires with greater diameter will give better resistance against external wear. Moreover, because of the fact that there is no

mutual crossing of the wires in the strands, the internal wear is far less than in the normal construction.

Another advantage of the "Seale" construction is the closed design. The grooves of one layer are sealed by the wires of the following layer. This gives better protection against penetration of moisture and dirt.

Generally, a great variety of factors influences the durability of a wire rope, and thus it takes sometimes years of investigation and experimentation to find the correct type of wire rope for a certain job.

Influence of construction on durability of wire rope

(a) Wire rope, type 6 × 37 + 1 steel core and 3 × 34 + 1 steel core, formerly used in a *portal-crane* lasted about 1 month. This rope was replaced by a non-spinning wire rope, type 18 × 4 + 1 steel core; its life was about 2 months. This rope was in turn replaced by a non-spinning Seale-type wire rope, which proved to be serviceable for 6-9 months.

The improvement found cannot be completely accounted for by the Seale construction, since the wire diameter of the original rope and that of the outer wires of the present rope are the same, *viz.* 1.4 mm. The greater durability must therefore be attributed to the non-spin character and greater flexibility, and to the fact that, owing to the Seale construction, the diameter of the outer wires was not decreased despite the much greater number of wires, while the internal wear greatly decreased.

(b) Almost all the cranes in our plant, and especially the *railway cranes*, are used continuously and very intensively. The motor-driven cranes that were obtainable during the first years after the war showed many imperfections, which resulted in a wire rope becoming unserviceable after about one week. The consumption of wire rope increased still more when steam-driven cranes were converted into motor-driven cranes, the latter operating less smoothly. Where possible, the diameters of the sheaves were increased and the sheaves provided with ball bearings to reduce the friction and consequently the stress in the wire ropes. The wire ropes of 17 mm were replaced by wire ropes of 20.6 mm type 6 × 41 + 1 hemp core "Seale", and consequently the sheave grooves had to be enlarged, because the profile of the groove is of great influence on the life of the wire rope. The radius of the groove should be 1.05-1.15 times the rope radius. If the groove radius is smaller, jamming occurs. On the other hand, if the radius of the groove is more than 1.15 times the rope radius the wire rope is insufficiently supported, and this causes overloading of the wires.

Further, the roughly bent strips between the sheaves were replaced by correctly fitting, turned rings. This arrangement prevented the wires from being drawn between the sheaves. Finally, by changing the brake-linings, a far smoother operation of the motor-driven cranes was achieved. As a result of these changes the durability of the wire ropes has reached an average of 3 months.

(c) The *buggy* used for transferring the hot slabs from the slab-reheating furnaces to the mill, is moved by means of a wire rope. Formerly this wire rope consisted of 6 strands made of 37 wires each (diam. 0.95 mm) + 1 hemp core. The wire rope was exposed to high temperatures, with the result that the greasy hemp core deteriorated.

In this way the strands, lacking the support of the core, were subjected to severe internal wear. The rope was replaced by a wire rope of the Seale type 6 × 19 + 1 independent wire rope core (diam. 1.6 mm). As a result, the service life was extended from 3 to 6 months.

Sealing of a pump shaft

A deep well pump, driven by an electromotor at ground level, consists of a long vertical stainless steel shaft sealed with a stuffing box containing greasy cotton packing. The gaskets caused severe wear of the shaft so that after only 6 months the top end

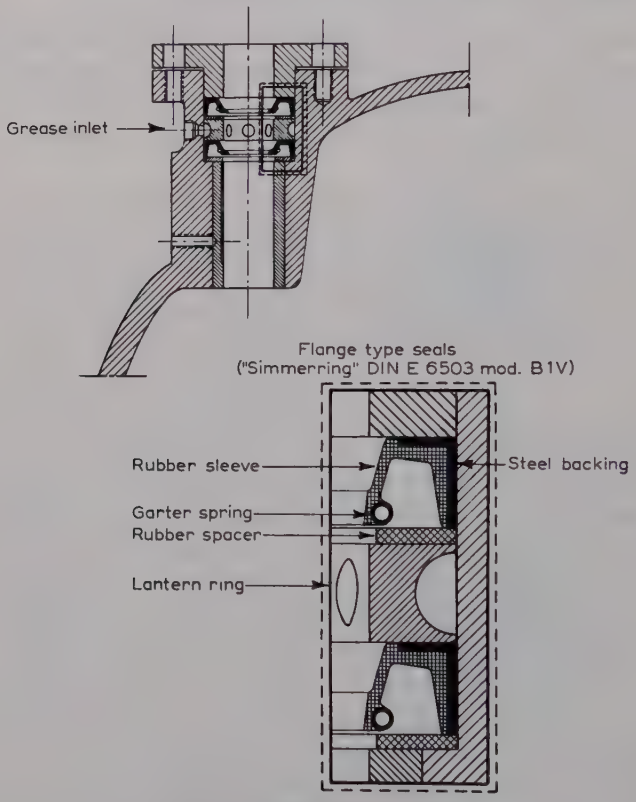

Fig. 2. Pump shaft sealing.

of the shaft had to be renewed. Further, it required much attention to keep the stuffing box in proper condition.

The gaskets were removed and replaced by a more efficient sealing device in the form of "flange type" seals. The wiping lip of the seal is pressed very lightly against the shaft by means of a carter spring. Two seals are inserted. Between the seals a lantern ring is placed, through which the lubricant, a water-repellent grease, is introduced (see Fig. 2).

After 9 months of continuous service, both seal and shaft showed no wear. The only maintenance consists of applying grease occasionally.

Bearings in dusty surroundings

Much trouble was experienced with a roller bearing of a coke screen in the coke-screening plant. The screen is supported by two rows of 11 spiral springs, each mounted on a frame, which rests upon rubber vibration-dampers.

The screen shaft runs in two roller bearings, which are mounted on the frame. The speed was 930 rev./min.

The screen movement is caused by 2 eccentric parts of the shaft running in the two roller bearings. Formerly, those bearings were cylindrical roller bearings, one of them fixed axially and the other one free to move in an axial direction. The bearings were lubricated with grease. Despite the labyrinth seal, coke dust penetrated inside the bearing, causing failure of the rollers, raceways and retainers. The fixed bearings especially had a tendency to run hot. The service life lasted from 1 week (minimum) to 6 months (maximum). Then a few modifications were made.

(a) The speed of the shaft was reduced from 930 to 880 rev./min.; this resulted in a quieter running of the screen.

(b) Grease lubrication was replaced by an oil-mist lubricating device, operating with compressed air. Owing to the air pressure in the bearing, entrance of dust is now prevented.

(c) The fixed cylindrical roller bearing was replaced by a double-row barrel bearing. In this way a thrust load could be supported in either axial direction.

The service life of the new bearing under continuous operating conditions was 14 months.

Wear in tubes

In the tube foundry a mixture of pulverized coke, clay, and water, is continuously pumped through tubes, and during service it becomes contaminated with sand. This highly abrasive mixture caused severe wear in the metal tubing.

The abnormal wear was prevented by replacing the metal parts by rubber tubing or by coating them with rubber. Other measures to prevent abnormal wear in similar circumstances are:

1. Avoiding sharp curvatures and abrupt changes in diameters.
2. Keeping the flow speed (V) low.

The influence of these measures on the service life can be seen from the following data:

TABLE I

Tubes	*Service life hours*
Mainline (rubber) diam. 40 mm, $V = 0.7$ m/sec	30.000
Hose-pipe (iron)	1.500
Hose-pipe (lined with rubber)	>18.000
2″ Plug valve (bronze) $V = 0.5$ m/sec	1.500
2″ Plug valve (lined with rubber)	>6.000
1″ Tee (iron) $V = 1.8$ m/sec.	400
2″ Tee (lined with rubber), $V = 0.5$ m/sec	>8.000

Received April 25, 1957
Accepted June 19, 1957

A REVIEW OF BOUNDARY LUBRICATION*

C. B. DAVIES

Thornton Research Centre, "Shell" Research Ltd., Chester (England)

INTRODUCTION

Whenever a fluid film is not maintained between sliding surfaces the contacting "boundaries" of the bodies in relative motion suffer wear, usually including some transfer of material of each to the other. Boundary lubrication controls this damage by interposing a solid barrier. This review deals with the relative merits of the different types of barrier and how they are put in place through physical and chemical agencies.

Although in the practice of lubrication, surface damage is almost always a more important factor than the size of the coefficient of friction, many of the papers allocated to this section of the Conference have described the attributes of various boundary lubricants in terms of their effect on friction, which is an insensitive index (RABINOWICZ[23]; GRUNBERG AND CAMPBELL, Paper 65)** of damage. Whilst a good boundary lubricant, in comparison with a poor one, may reduce the coefficient of friction severalfold, it is much more significant that interfacial damage may be reduced a thousandfold. Similarly a severalfold difference in damage may be accompanied by an imperceptible change in friction. Like friction, the extent of the damage depends not only on the quality of the boundary lubricant, but also on the nature of the moving surfaces to a depth which is considerable on an atomic scale.

DIRECTLY APPLIED SOLID BOUNDARY LUBRICANTS

Graphite and molybdenum disulphide

Some surfaces have boundary lubricants built into their skin, cast iron being the most widely used material in this class. On a run-in cast iron surface, graphite is smeared out with its cleavage planes parallel to the direction of sliding (FINCH[15]). Graphite is a crystalline substance having a layer structure, that is, strong bonds

* Condensed from the preprint presented on October 2nd, 1957, at the Conference on Lubrication and Wear arranged by the Institution of Mechanical Engineers, London. Reprinted in *Wear* by permission of that Institution. The full text of this review will be published in the Official Proceedings of the Conference.

** Normal references are numbered.

The Appendix gives an alphabetical list of authors of papers read at this Conference.

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holding the atoms together within each layer and quite weak adhesion between these layers when piled together. Possession of such a layer structure contributes towards making a substance a good boundary lubricant but, in itself, is not an infallible guide. Above all a boundary lubricant must resist penetration of the interface by either of the approaching surfaces. Because of this, and the fact that boundary lubrication is a regime imposed when the severity of operating conditions exceeds the limit for fluid film lubrication, it is logical to accept the considerable experimental evidence that for full effect a boundary lubricant must remain solid. The resistance of this solid should be high against intrusion from a direction perpendicular to the plane of the interface, and therefore a layer structure material will have to be orientated with its sheets of strongly bonded atoms parallel to the interface.

Several investigators have asserted that for most practical duties the boundary lubricant must be distributed so that the whole interface is continuously protected by a layer many atoms or molecules thick. But HIRST AND LANCASTER[19] propose that when surface deformation is not unrealistically exaggerated thinner and even patchy layers may be effective.

BISSON, JOHNSON AND ANDERSON (Paper 23) stress the advantages of, and special steps necessary to ensure effective attachment of a boundary lubricant on to one or both of the sliding surfaces. It is proposed that graphite works unconditionally when attached, whereas moisture or similar films are essential on loose graphite.

At room temperature, and a little above, graphite sprinkled on Inconel gave relatively low friction which rose steeply as the temperature increased beyond 100°C (212°F). This accords with the belief (SAVAGE[24]) that graphite lubricates only as long as adsorbed films such as water can be retained. Persisting with the temperature rise, friction was still high at 343°C (649.4°F) but dropped somewhere between 427°C (800.6°F) and 454°C (849.2°F), and at 538°C (1000.4°F) was as low as at room temperature, subject to adequate graphite replenishment offsetting its oxidation. The authors conjectured that graphite, free from adsorbed films, lubricates if keyed on to a metal surface through interaction with an adherent oxide layer. They found that the right sort of oxide layer could be formed by direct reaction with oxygen at a temperature related to the ease of oxidation of the sliding metals. Mixing graphite with a soft metal oxide such as cadmium or lead oxide, improved the boundary lubricating performance at lower temperatures. High wear of a graphite specimen rubbing against oxide-coated metals is described as confirming, although not explaining, the interaction asserted.

In contrast, DEACON AND GOODMAN (Paper 17) believe that adequate and correctly orientated attachment may occur readily through the agency of sustained rubbing, which itself automatically tends to set cleaved plates of graphite parallel to the surface, where they become embedded because of their extreme hardness in the direction perpendicular to the cleavage plane.

This seems consistent with the conclusions of BISSON, JOHNSON AND ANDERSON (Paper 23) on the success of an attached layer. DEACON AND GOODMAN (Paper 17), however, attributed the failure of the layers which were not "dry-rubbed" to less effec-

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tive covering of the surface and to graphite removal by low temperature oxidation of thin areas of this more patchy type of cover.

The molybdenum disulphide layer structure is an improvement on graphite in that neither special circumstances favouring attachment to a metal surface nor adsorbed films on the solid lubricant seem necessary for its boundary lubricating effect. BISSON, JOHNSON AND ANDERSON (Paper 23), using a continuous airborne "dust", found low friction in their ball-bearing test in air up to 400°C (752°F), beyond which oxidation caused failure through abrasive molybdenum trioxide and sulphur compounds which attacked the bronze cage. Blanketing with nitrogen resulted in low friction up to 538°C (1000.4°F). DEACON AND GOODMAN (Paper 17) observed low friction on platinum in air up to 340°C (644°F), their assessment of the temperature at which rapid destruction of molybdenum disulphide by oxidation set in.

ROWE (Paper 5) used a silica envelope around an apparatus for measuring friction at low speeds and loads in a good vacuum or other controlled atmosphere after rigorous high temperature cleaning of the specimen surfaces. He found that as a boundary lubricant, rubbed on or chemically formed in place, molybdenum disulphide kept friction low up to 800°C (1472°F) *in vacuo* and therefore without the help of oxygen, water vapour or a metal oxide film. Work by MIDGLEY[21] has in fact suggested that in contrast with graphite the less the water vapour, etc., adsorbed on molybdenum disulphide the better its boundary lubricating performance. Despite the impression from this work that there is no incentive for special steps to ensure attachment of molybdenum disulphide to surfaces, particular merit has been claimed elsewhere for bonding before use. An effective way of doing this (BARWELL AND MILNE[1]; MITCHELL AND FULFORD, Paper 27) on steel is to phosphate the surface first and then bake the boundary lubricant into the surface layer after impregnating this with a suspension of the molybdenum disulphide in a suitable liquid which evaporates or "cures" during the heat treatment.

PTFE, the best of the plastics

A recent development (BOWDEN AND LOVE[7]; MITCHELL, Paper 74) related to the effectiveness of the lead phase in copper–lead bearings is the use of a unique synthetic non-metallic solid, polytetrafluoroethylene, built into a porous working surface of high thermal conductivity such as copper. At low speeds PTFE slides on itself or on metals with a coefficient of friction in the lowest range observed for boundary lubrication, about 0.05. At higher speeds friction rises (FLOM AND PORILE[17]) to values common for other plastics. This higher friction also tends to persist when low-speed conditions supersede the high-speed running. It is likely this is a thermal effect caused by a structural transition allowing more intermolecular cohesion and promoted by the extremely poor heat conductivity (BOOSER, SCOTT AND WILCOCK, Paper 8) of PTFE. However, it is important to emphasize that whilst friction rises with speed, PTFE may remain a good boundary lubricant (ATKINS AND GRIFFITHS, Paper 19; MITCHELL AND PRATT, Paper 101) with respect to preventing surface damage up to about 400°C (752°F) beyond which temperature rapid bulk decomposition of this plastic starts.

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OIL-BORNE BOUNDARY LUBRICANTS

Suspensions of the ready-made boundary lubricants, graphite, molybdenum disulphide and PTFE

So far, we have considered built-in boundary lubricating layers on working surfaces. In many practical applications such surfaces may perform even a major part of their duty protected by a fluid film due to the presence of a lubricating oil. The boundary layer is used to tide the surface over emergencies such as excessively heavy load or low sliding speed. An alternative is to build into the lubricating oil itself some means of providing a similar emergency protective. Several of the boundary lubricants already mentioned, for example, graphite, molybdenum disulphide and PTFE, are effective under certain boundary conditions when merely suspended in the fluid which itself is designed to provide the hydrodynamic lubrication. To be effective in a boundary emergency during an otherwise hydrodynamic regime there must be a timely build-up of a durable layer of the low shear strength solid on the critical areas of the rubbing surfaces. There are practical lubrication problems, for example, vehicle rear-axle hypoid gears, where this condition cannot be fulfilled by suspended, ready-made boundary lubricants, which therefore fail.

Significance of physical adsorption and molecular orientation

There has been considerable controversy about whether purely physical adsorption itself confers boundary lubricating properties. When a liquid contains polar molecules which adsorb physically at a metal surface but may not react chemically, there have been demonstrations (DERYAGUIN AND KARASSEV[14], CRIDDLE[12]) of aligned, semi-solid layers existing up to about 1000 Å thick, although such "structures" may be unstable at high rates of shear (BONDI[5]).

The effect on the coefficient of friction of the length of a shearing, or molecule-aligning channel constituting the boundary region, forms part of an investigation described by LAZAREV AND DERYAGUIN (Paper 11). They used an apparatus called a wire tribometer, rather like a crossed-cylinders machine with one cylinder, the wire, bent partly round the other.

With a mineral white oil, highly refined to remove polar molecules, friction was not affected by the length of the sliding contact. The authors suggest that the behaviour indicates absence of molecular orientation effects with the oil.

With oleic acid used neat at moderate shaft speeds, an increase in contact arc decreased the friction. The authors assert that the longer the path of contact the greater the proportion of fatty acid molecules tending to be bent into what they consider the most effective orientation, namely, with length tangential to the contact arc. The authors support a suggestion put forward by BEECK, GIVENS AND SMITH[2] that, whilst in a relatively quiescent liquid medium, long-chain polar compounds form highly oriented surface layers with anchored heads but free tails perpendicular to metal surfaces, they promote the formation of molecular-dimensioned material wedges

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by inclining their long tails as sliding gets underway. In a nominally boundary regime BEECK referred to this as the establishment of quasihydrodynamic lubrication.

CLAYFIELD, MATTHEWS AND WHITTAM (Paper 1) have obtained a measure of the tendency of different mineral oils to spread on a steel surface or of the force of attraction between a steel surface and the oils. They compare these "spreading pressures" with the ability of the different oils to prevent transfer of metal from the surface of a bronze disc to a steel disc in a "disc machine" simulating the sliding and rolling or sweeping action in gear contacts. The discs rotated in the same plane and were constrained in edge-to-edge contact with continuous slip at the interface owing to the imposition of different peripheral speeds. Out of five oils the two with highest spreading pressure were successful in preventing bronzing of the steel. High spreading pressure is associated with physical adsorption of minor constituents of the oil, and one interpretation of the results is that such adsorption promotes effective boundary separation of the steel and bronze even at the quite considerable sliding speeds of the order of hundreds of ft./min involved in the test.

Much experimental evidence has been produced in favour of the overwhelming importance of chemical reaction. However, considering the lowest degree of boundary lubrication, even chemically inert liquids leave a film on sliding surfaces after the collapse of fluid lubrication, and certainly have some boundary lubricating effect. For example, the effect is greater for hydrocarbons than for silicones of roughly equal molecular size. There is in this and any comparison of hydrocarbons with silicones or other synthetic oils, a somewhat confusing issue of the differing tendency (BOELHOUWER AND TONEMAN, Paper 38) of the fluids to approach the solid state under the influence of pressure (CLARK, WOODS AND WHITE[11]) or indeed other agencies. The hydrocarbons become solid more readily than silicones under the influence of pressure alone. However, BROPHY, MILITZ AND ZISMAN[10] found that if silicone fluids are induced chemically to polymerize on a surface to a plastic solid, very satisfactory boundary lubrication is achieved.

Fatty oils, such as castor oil (WILFORD, Paper 29) and tallow oils, are better boundary lubricants than hydrocarbons of comparable molecular size. Several synthetic oils which are chemically and physically similar to the fatty oils are also found to be better lubricants than hydrocarbons for moderate sliding speeds (DAVID, HUGHES AND REECE[13]). Although the formation of metal soaps, directly or through traces of acids derived by oxidation or hydrolysis of such esters has been postulated (BOWDEN AND MOORE[8]), it is puzzling that the performance of, say, castor oil in a bronze worm-gear cannot be matched by addition of appropriate fatty acids to hydrocarbon oils and that hydrocarbons are not matched by similar additions to silicones.

Suspensions of ready-made metal soaps

Metal soaps may be prepared in bulk and dispersed in a hydrocarbon lubricating oil, the most familiar type of end product being a grease. The soap is not put into the oil in this instance to impart boundary lubricating properties, but rather to form a fibrous phase capable of conferring the rheological properties required in grease lubri-

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cation. However, as they expected from an analogy with the performance of metallic soaps formed in place on surfaces, MILNE AND COOKE (Paper 62) have shown that the soap phase of a grease can contribute to boundary lubricating properties.

Lead naphthenate is a metal soap sometimes dissolved in small quantities in an oil to improve boundary lubrication. Positive benefits seem to have been consistently shown only when films of lead naphthenate contain admixed inorganic substances, such as lead sulphide or even metallic lead itself. These arise (SIMARD, RUSSELL AND NELSON[25]; CAMPBELL, Paper 61) by reaction of the lead soap with sulphur compounds or other additives present, probably catalysed by the metallic surfaces to be protected. It can be conjectured that the inorganic inclusions postpone failure after the soap itself melts. In differentiating such behaviour from that of other metal soaps formed in place by fatty acids on reactive metals, lead naphthenate has sometimes been given the peculiar title of "a mild extreme-pressure agent". Incidentally, sodium soaps are of much higher melting point than most others, and this is significant regarding their application for wire-drawing (WISTREICH, Paper 4), where they are also often filled with various inorganic materials to extend the solid or semi-solid range. Incorporation of inorganic substances in boundary layers introduces the principle on which extreme-pressure lubrication is based.

Extreme-pressure lubrication

In trying to sort out such definitions, it must be assumed that extreme-pressure conditions were meant to refer to a severity arising not from pressure but from temperature (BLOK[4]), since there is little reason to believe that an increase in pressure alone makes it difficult for a solid layer of boundary lubricant to work. Progressively rising temperature, on the other hand, will eventually overtake the melting point of the protective or lead to its destruction in other ways, such as through oxidation. In general, protectives which can be classed as organic compounds have a structure conferring a low melting point corresponding to the 100° to 120°C (212° to 248°F) failure temperature for most soaps, However, a severity involving a temperature of many hundreds of degrees C can be withstood by purely inorganic films of substances of quite high melting point, therefore known as "extreme-pressure lubricants". For example, if certain chlorinated hydrocarbons are dissolved in a lubricating oil, progressive increase in the severity of boundary conditions on steel results in chemical reaction with the surfaces, yielding a film consisting of a complex mixture of iron chlorides and oxychlorides (FINCH[15]). As discussed by ROWE (Paper 5), some of these chlorides have a layer structure and behave as low shear strength solids up to 300° to 400°C (572° to 752°F), at which point melting and/or decomposition spoil their protective effect.

Sulphide films can also be formed (CAMPBELL, Paper 61) in place by a thermally triggered reaction of a suitable sulphur compound or sulphur itself dissolved in a lubricating oil working with surfaces such as steel. Sulphides have higher melting points than the corresponding metallic chlorides and therefore may continue to protect boundaries beyond the severity limit tolerable with chlorides. In fact, sulphides of iron appear capable of lubricating steel up to about 800°C (1472°F) (BOWDEN[6]).

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The higher ultimate failure temperature of sulphides is offset by a higher shear strength than corresponding chlorides. It is possible to think of each type of boundary lubricant with its own appropriate realm of effectiveness handing on the task at its frontiers, and this picture fits in with the practical success, in applications such as hypoid gears and metal working, of oils containing metallic soaps or their precursors, such as fatty acids, together with chlorine and sulphur compounds capable of forming extreme-pressure layers. The reactivities of those agents used together in service suggest that all minor boundary emergencies are dealt with by the very low shear strength metal soaps and the most severe crises by the sulphides, with the chlorides playing an intermediate or perhaps mutually enhancing (PRUTTON, TURNBULL AND DLOUHY[22]) role with sulphides.

The speed of formation of the protective film is of the greatest importance and, as may be expected, it is possible for incipient lubrication emergencies to build up too quickly for the timely formation of a boundary film by chemical reaction with the sliding surfaces. For example, with a given additive oil, scuff-limited load-carrying capacity in gears (DAVID, HUGHES AND REECE[13]) is reduced as speed increases, and similarly there is an upper limit of metal cutting speed beyond which e.p. cutting oils fail (MERCHANT[20]). Higher chemical activity would help to meet this challenge, but a limit is set by the need to avoid materials which are actively corrosive and therefore objectionable at normal bulk oil temperatures.

ROWE (Paper 5) with his controlled-atmosphere apparatus confirmed the almost invariable increase in friction on thoroughly cleaning a surface. Then, bypassing practical extreme-pressure lubricants, he used reagents such as chlorine to form surface films chemically from the atmosphere around the friction specimens. In this way he illustrated the effectiveness as boundary lubricants of all the following layer-structure or similarly constituted films: copper soaps, uranium and tungsten disulphides, titanium di-iodide, chromic chloride and tungsten hexachloride. The ultimate failure temperature of these films in friction tests was in good agreement with their melting or decomposition point.

Although the films formed by chemical reaction on rubbing surfaces can be so effective, the extent of the reaction in practice is very small. If surfaces are so severely worked that the protective is removed, reaction again sets in to repair the film, but in service repeated sequences of this sort on any large scale tend to be confined to a running-in period, during which they become progressively less drastic. Since a sensible compromise can be made between adequate and excessive corrosivity, a comparison with other methods of establishing a boundary lubricating layer commends formation through chemical reaction at a surface as an ideal device for getting the layer just where and when it is wanted and correctly orientated.

Apart from fatty acids, chlorine and sulphur compounds, and some rather less practical materials containing rarer elements, phosphorus is the only generally important element whose presence in a molecule may contribute to potential boundary lubricating properties through a product of chemical reaction at a sliding surface. Whilst there is considerable evidence, notably from electron diffraction work, about what

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reaction processes of fatty acids, sulphur and chlorine compounds are effective in boundary lubrication, the behaviour of phosphorus has not been so systematically studied. It has been suggested (BEECK, GIVENS AND WILLIAMS[3]), with supporting evidence from electron diffraction, that on steel it forms a comparatively fusible eutectic between iron and iron phosphide which may assist in smoothing the surface, "chemical polishing", to distribute the load over a bigger area. FINCH AND SPURR[16], although not directly advocating polishing, proposed that extreme-pressure sulphide films on steel protect in the act of liquefying and smearing as a eutectic with an oxide.

It has been stressed that boundary lubricants should be low shear strength solids, and metal soaps, chlorides and sulphides have been recommended. Already this has seemed inconsistent in that sulphides of many of the metals in question are often not low shear strength solids, and it must be added that further steps away from low shear strength boundary lubricants can be taken in some instances without losing all the benefit sought. For instance, with his controlled-atmosphere apparatus ROWE (Paper 5) confirmed that oxide layers formed by direct reaction with oxygen or often alternatively with moisture, prevented seizure, admittedly at light loads, or reduced the very high friction observed with clean copper, silver, titanium and chromium, but in no case gave low friction. Oxides of metals are almost invariably higher shear strength materials than sulphides and, whilst from the standpoint of friction will be less good as boundary lubricants (GREENHILL[18]), their refractory nature may extend to higher temperatures the protection afforded against excessive damage. When the shear strength of the oxide is not less than that of the parent metal, damage may still be reduced by the presence of the oxide which lowers the strength of the minute welded junctions forming between sliding surfaces (WILSON[26]). Oxides, even on their own, are therefore better than nothing and to their presence in a uniform, strong and adherent state is owed (FINCH[15]) the practicability of attaching further protectives.

When relying on the oxide alone, aluminium (WILSON[26]) requires a robust film to compensate for the extreme difference in mechanical properties of the soft metal and its brittle oxide. WRIGHT AND SCOTT (Paper 60) examined the influence of the nature of an oxide film on boundary friction and wear of aluminium with the chemically inert lubricant, medicinal paraffin, and the reactive type such as oleic acid. A porous film co-operated with the lubricants, whilst an impervious oxide film inhibited boundary lubrication. The authors consider that even with quite thick films of good mechanical properties, such as provided by anodizing, high sliding temperatures and impact loads would need to be avoided for satisfactory practical service. It has been pointed out that in unfavourable circumstances, metals, including steels, may acquire a mechanically poor oxide film, also capable of spoiling (HIRST AND LANCASTER[19]) the performance of potentially effective boundary lubricants.

Summing up, it appears not to be over-simplifying or neglecting too much evidence to conclude that a boundary lubricant has to interfere with inter-metallic welds across the interface between sliding surfaces, and to do this, a solid incapable of taking part in the welds must be established at the surface, its success depending on a combination

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of low shear strength and resistance to being penetrated and fluxed away by melting, decomposition or oxidation.

The state of knowledge about the mechanism of boundary lubrication is well advanced but cannot be represented as responsible for dramatic advances in the practice of lubrication. Whilst an empirical approach has guided the broad selection of the successful lubricants of today, theory has facilitated arranging details of application; for example an appreciation of the need to avoid over-heating a boundary layer of PTFE led to using this substance in a metal matrix. As a result of technical progress such as the development of the aviation gas turbine and nuclear energy, sliding at high temperatures is becoming increasingly important and fundamental knowledge must be extended and exploited towards further advances in tailor-making boundary lubricants which will not in themselves impose a limit on the efficiency and range of application of engineering equipment. Solid lubricants are available to withstand temperatures up to, say, 400°C (752°F) in air, but there is an urgent need for new liquids stable at such temperatures and suitable as carriers for boundary lubricating additives including extreme-pressure agents. A liquid carrier offers considerable advantages over directly applied solids in that cooling is facilitated and also a hydrodynamic component is encouraged in the overall lubrication duty, which so often in practice involves boundary conditions as only a temporary though exacting emergency.

ACKNOWLEDGEMENT

The author wishes to thank colleagues in "Shell" Research, Ltd., and the Conference Organizing Committee for help with this review.

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APPENDIX

Papers read at the Conference on Lubrication and Wear, October, 1957. To be published in the Official Proceedings of the Conference.

ATKINS, B. R. AND GRIFFITHS, D. P., Paper 19, "Electrical Sliding Contacts and Their Behaviour at High Altitudes".

BISSON, E. E., JOHNSON, R. L. AND ANDERSON, W. J., Paper 23, "On Friction and Lubrication at Temperatures to 1000°F with Particular Reference to Graphite".

BOELHOUWER, J. W. AND TONEMAN, Miss L. H., Paper 38, "Viscosity-Pressure Dependence of Some Organic Liquids".

BOOSER, E. R., SCOTT, E. H. AND WILCOCK, D. F., Paper 8, "Compatibility Testing of Bearing Materials".

CAMPBELL, R. B., Paper 61, "Sulphur as an Extreme Pressure (E.P.) Lubricant".

CLAYFIELD, E. J., MATTHEWS, J. B. AND WHITTAM, T. V., Paper 1, "Importance of Oil-Metal Adhesion in Lubrication".

DEACON, R. F. AND GOODMAN, J. F., Paper 17, "Orientation and Frictional Behaviour of Lamellar Solids on Metals".

GRUNBERG, L. AND CAMPBELL, R. B., Paper 65, "Metal Transfer in Boundary Lubrication and the Effect of Sliding Velocity and Surface Roughness".

LAZAREV, V. P. AND DERYAGUIN, B. V., Paper 11, "Investigation of Boundary Lubrication in Kinetic Friction by Means of a Wire Tribometer".

MILNE, A. A. AND COOKE, W. L., Paper 62, "On the Influence of Grease Structure on Boundary Lubrication".

MITCHELL, D. C., Paper 74, "Wear of PTFE Impregnated Metal Bearing Materials".

MITCHELL, D. C. AND FULFORD, B., Paper 27, "Wear of Selected Molybdenum Disulphide Lubricated Solids and Surface Films".

MITCHELL, D. C. AND PRATT, G., Paper 101, "Friction, Wear and Physical Properties of Some Filled PTFE Bearing Materials".

ROWE, G. W., Paper 5, "Vapour Lubrication and the Friction of Clean Surfaces".

WILFORD, A. T., Paper 29, "Lubrication of Road Vehicle Engines and Worm-driven Axles with Particular Reference to Vehicle Fuel Consumption".

WISTREICH, J. G., Paper 4, "Lubrication in Wire Drawing".

WRIGHT, K. H. R. AND SCOTT, Mrs. H. M., Paper 60, "Frictional Behaviour of Anodized Aluminium Surfaces".

The M.S. of this paper was received at the I.M.E. (London) on September 13th, 1957.

Literature and Current Events

The purpose of the following sections is to build up gradually an information centre on the various aspects of wear. Contributions *in English* are invited. All items of these 6 sections will be finally included in a separate "Volume-Index of Literature and Current Events":

1. *Systematic Abstracts* on current literature for 1957 prepared by Battelle Memorial Institute begin to appear in this issue. Systematic abstracts covering the years 1955 and 1956 will also be published in Volume 1.

2. A selected number of *Authors' Abstracts* (in English), giving more detailed information than the "Systematic Abstracts", will be accepted for publication.

3. *Bibliographies* on work in specialized fields or on work in languages other than those of this Journal, will also be published.

4. *Recent Events* should assist readers in following progress reported in lectures and in finding the names and addresses of specialists and technical groups or societies interested in the various aspects of friction, lubrication and wear.

5. *Forthcoming Events* will give notice of conferences, meetings, or discussion panels of interest to readers of *WEAR*.

6. *Notes on Contributors* should facilitate personal contacts between workers interested in wear problems.

Systematic Abstracts of Current Literature

Prepared by Battelle Memorial Institute, Columbus, Ohio, U.S.A.

Reprinted from Battelle Technical Review
Jan.-Oct. 1957

The space available for this purpose is insufficient to mention all papers of potential interest to readers of WEAR. These Abstracts are taken from the selection made by Battelle Staff. Papers reported already as Authors' Abstracts are *not* included in this survey. A special Subject Index will combine all abstracted matter at the end of this volume.

A further selection of Abstracts from 1954—1956 will be published in future issues as an additional feature of these Abstracts of Current Literature.

The classification is meant only to assist readers in tracing a subject; it may be rearranged in future issues. Within each sub-group the Abstracts are systematized alphabetically. (Ed.)

1. Friction

1.1. *General and Fundamentals*

The Onset of Friction in Helium II.
D. F. Brewer, D. O. Edwards, and K. Mendelssohn. *Philosophical Magazine*, v. 1, ser. 8, Dec. 1956, p. 1130-1132.

The Effect of a Tangential Force on the Contact of Metallic Bodies.
J. S. Courtney-Pratt and E. Eisner. *Royal Society, Proceedings*, v. 238, ser. A. Jan. 29, 1957, p. 529-550 + 1 plate.
Gold, Pt, Sn, In, and mild steel specimens were examined.

Pressure Transmission in Liquid Films.
Edward Dawson. *Franklin Institute, Journal*, v. 262, Oct. 1956, p. 255-263.
Experiments in which sliding of steel blocks in oil-filled chamber was temporarily stopped by conditions of hydraulic unbalance and friction resulting from delay in transmission of pressure increments.

Dependence of the Coefficient of Friction on Velocity. (in Russian)
V. D. Kuznetsov and V. I. Flerov. *Doklady Akademii Nauk SSSR*, v. 113, Apr. 11, 1957, p. 1050-1052.
Effect of speed on scoring during rubbing of steel on steel and a hard alloy on steel.

Friction and Lubrication.
N. Pilpel. *Research*, v. 10, Apr. 1957, p. 138-144.
Review of recent advances in knowledge of theory and surface properties.

A General Theory of the Surface Friction of Solids.
C. Rubenstein. *Physical Society, Proceedings*, v. 69, no. 441B, Sept. 1956, p. 921-933.
Theory is based on the assumptions that the adhesion theory of friction is valid and that the asperities, at which contact occur, deform according to the law stress α (strain)$^{\times}$.

The Variation of Friction With Velocity.
R. T. Spurr and T. P. Newcomb. *Physical Society, Proceedings*, v. 70, no. 446B, Feb. 1957, p. 198-200.
The friction of a bituminous material decreases with increasing sliding velocity; this decrease is due to the creep behavior of the material.

The Mechanism of "Free" Rolling Friction.
D. Tabor. *Lubrication Engineering*, v. 12, Nov.-Dec. 1956, p. 379-386.
A study of the mechanism of rolling friction in the elastic range suggests that the major source of "free" rolling friction is elastic hysteresis losses in the solids themselves.

The Drag on a Circular Cylinder Placed in a Stream of Viscous Liquid Midway Between Two Parallel Planes.
Yorisaburo Takaisi. *Physical Society of Japan, Journal*, v. 11, no. 10, Oct. 1956, p. 1092-1095.

Mutual Friction in a Heat Current in Liquid Helium II. I. Experiments on Steady Heat Currents. II. Experiments on Transient Effects.
W. F. Vinen. *Royal Society, Proceedings*, v. 240, ser. A, Apr. 24, 1957, p. 114-143 + 2 plates.

1.2. *Materials*

Friction of Rubber on Rough Surfaces.
F. W. Boggs and W. P. Riemen. *Rubber Age*, v. 81, July 1957, p. 613-618.
A proposed mechanism by which rubber is lost, permitting a prediction of the merit of tread materials on laboratory data.

Über trockene Reibung bei einigen Aluminiumlegierungen und Stählen.
Dry Friction of Some Aluminum Alloys and Steels.
F. Bollenrath and H. Grefkes. *Aluminium*, v. 33, Apr. 1957, p. 234-240.
Coefficients of static and cold welding friction depend on materials and conditions, while those of pure sliding friction are determined by the properties of the material in the surface layers.

Calculation of the Contribution Made by Grain-Boundary Sliding to Total Tensile Elongation.
H. Brunner and N. J. Grant. *Institute of Metals, Journal*, v. 85, Oct. 1956, p. 77-80.
Severe stress concentrations occur at the triple points whenever grain-boundary sliding takes place. An equation is derived which permits calculation of the elongation of a tensile specimen caused by sliding along any particular grain boundary.

Fatigue of Metals Under Contact Friction. (in Russian)
V. S. Ivanova, and I. A. Oding. *Izvestiia Akademii Nauk SSSR, Otdelenie Tekhnicheskikh Nauk*, no. 1, Jan. 1957, p. 95-102.
Decrease in fatigue limit of Cr-Ni-Mo steel during contact friction is explained as due to electroerosion from thermoelectric currents produced by changes in contact resistance. This erosion leaves vacancies in the crystal lattice. Fatigue limit can be raised by changing the direction of the thermoelectric current through proper choice of materials or by inducing a counter-current.

The Relation Between Coefficient of Friction, Conductivity and Static Electrification Induced by Friction in Cellulose Acetate Yarns.
G. Quintelier, M. Warzée, and R. Sioncke. *Textile Institute, Journal (Proceedings)*, v. 48, Jan. 1957, p. P26-P39.
In order to avoid static troubles in processing, it is desirable that yarns have low coefficients of friction, but even more desirable that they have the largest possible conductivity.

1.3. *Machine Parts and Machinery*

Investigation of Causes of Low Wheel-to-Rail Adhesion and Possible Methods of Improving It.
F. G. Fisher and R. K. Allen. *ASME, Transactions*, v. 79, Feb. 1957, p. 377-388.
Running adhesions in excess of 26% can be maintained by the application of certain materials to locomotive drivers or to the rail.

Design Manual for Roller and Silent Chain Drives.
Jackson & Moreland. 95 pp. 1955. Association of Roller and Silent Chain Manufacturers, Detroit. (TJ1117 J13d Over.)
History of the chain drive; comparison of mechanical power drives; description of roller chains and sprockets; design principles; roller chain installation, lubrication, and maintenance; silent chain drives.

Use of Rolling Contact Bearings in Low Viscosity Liquid Metal Lubricants.
W. Markert, Jr. and K. Mildred Ferguson. *Lubrication Engineering*, v. 13, May 1957, p. 285-290.
Tests with bearings submerged in and lubricated by either liquid NaK, or liquid Na. Mechanism of bearing failure.

Étude de la température en milieu thermique limité dans les problèmes de frottement appliqués au freinage.
A Study of Temperature in a Limited Thermal Medium Applied to Friction Problems in Braking.
Jean Odier and Pierre Leutard. *Comptes Rendus*, v. 244, Feb. 25, 1957, p. 1141-1142.
A theoretical study of a formula expressing the increase of the average temperature of a rubbing surface during braking with constant slowing.

Measurement and Control of Chatter in Gear Drives.
C. E. Rose and G. F. Hadley. *Product Engineering*, v. 27, Dec. 1956, p. 168-171.
Gear drive chatter is analyzed with the Geiger Torsiograph. Equations are developed for computing speed variations and eccentricity. General recommendations are given concerning gear reducers and drive motors.

Distribution of the Surface Pressure Over the Friction Lining of Brakes With Rigid Shoes and Drums, and Efficiency of Such Brakes.
H. Schroder. *Acta Polytechnica (Mechanical Engineering Series)*, v. 3, no. 8, 1956, 44 p. (T1 Ac81 Vis.)

Friction Drive for Precision Positioning.
L. A. Smitzer. *Machine Design*, v. 29, May 30, 1957, p. 73-75.
Design factors and principles in the development of a friction clutch system for precision control of starting and stopping.

Friction Hoist Design Considerations.
G. L. Tiley. *Canadian Mining and Metallurgical Bulletin*, v. 50, June 1957, p. 326-333; *Canadian Institute of Mining and Metallurgy, Transactions*, v. 60, 1957, p. 176-183.
A concise account of the underlying principles of friction hoist design, and an attempt to develop a logical method of approaching the problem.

Friction in Cold Rolling.
C. T. van Rooyen and W. A. Backofen. *Iron and Steel Institute, Journal*, v. 186, June 1957, p. 235-244.
Both the radial-oblique pin and the surface reference-marker techniques are useful tools for exploring frictional conditions along the arc of contact. Experiments were performed on Al strip with roll surfaces prepared by grinding and also by sand blasting.

2. Lubrication and Lubricants

2.1. *General and Fundamentals*

General Purpose Greases.
Lubrication, v. 42, Oct. 1956, p. 125-132.
Serval types of greases are considered, including their composition, suitable working temperature ranges, properties, and uses.

Extreme Pressure Lubricants.
Lubrication, v. 43, June 1957, p. 65-76.
Theories of boundary lubrication. Evaluation tests and applications.

Lubrication. A Study of Its Action in Continuous Metal Deformation. I.
L. H. Butler. *Steel Processing and Conversion*, v. 43, May 1957, p. 269 + 7 pages.
Friction mechanism and theory; types of lubrication, requirements of lubricants for metal-deformation processes. (To be continued.)

Lubrication in the Presence of Nuclear Radiation.
J. G. Carroll and R. O. Bolt. *Lubrication Engineering*, v. 12, Sept.-Oct. 1956, p. 305-309.
Effects of pile radiation on the lubrication of bearings and gears using three special lubricants with unusual radiation stability.

Some Effects of Gamma Radiation on Commercial Lubricants.
J. G. Carroll and S. R. Calish, Jr. *Lubrication Engineering*, v. 13, July 1957, p. 388-392.
Several commercial oils and greases can be used in the presence of γ radiation for dosages of at least 10^8r. In general, the end effect of radiation on lubricants is similar to severe oxidation. Wear properties and load carrying capacity of certain oils are enhanced.

Solid Film Lubricants.
Ralph E. Crump. *Instruments and Automation*, v. 29, Nov. 1956, p. 2232-2236.
Application, technique, surface pretreatment, operational factors, and theoretical considerations.

Mise au point d'une méthode d'essai permettant de déterminer l'influence des lubrifiants sur le grippage des pistons dans les moteurs 2 temps à essence.
Developing an Experimental Method for Determining the Effect of Lubricants on Piston Seizure in Two Cycle Gasoline Engines.
A. Dyson. *Revue de l'Institut Français du Petrole et Annales des Combustibles Liquides*, v. 11, Nov. 1956, p. 1489-1495.

Yield Stress as a Factor in the Performance of Greases.
D. Evans, J. F. Hutton, and J. B. Matthews. *Lubrication Engineering*, v. 13, June 1957, p. 341-346.
Apparatus for measuring cone resistance value as a function of temperature. Use in defining quality of a grease.

Smøremidler i industrien.
Lubricants in Industry. Hans Goksøyr. *Teknisk Ukeblad*, v. 104, May 2, 1957, p. 363-366.
A study of modern requirements for lubricants. Hydrodynamic and boundary lubrication. Antifriction metals; types of bearing surfaces. Effects of additions of methacrylate polymers, polar molecules, silica polymers, phosphates, latex, and aromatic substances on the properties of lubricants.

2.2. *Materials*

Kolloidaler Graphit und sein Einfluss auf Reibung und Schmierung, besonders in Verbrennungsmotoren.
Colloidal Graphite and Its Effect on Friction and Lubrication in Internal Combustion Motors.
J. U. Augustin and Anna Maria D'Ans. *VDI Zeitschrift*, v. 99, Mar. 1957, p. 274-279.
Friction and wear; lubrication; adhesive and cohesive forces. (To be continued.)

Kolloidaler Graphit und sein Einfluss auf Reibung und Schmierung, besonders in Verbrennungsmotoren.
Colloidal Graphite and Its Influence on Friction and Lubrication, Especially in Combustion Engines.
Josef Udo Augustin and Anna Maria D'Ans. *VDI Zeitschrift*, v. 99, May 1957, p. 624-632.
Experiments show that colloidal graphite from lubricating oils precipitates on and in the working surfaces of cylinders in combustion engines. Electrolytic deposition of graphite on the surfaces of sliding parts gives a smooth and very adhesive protective layer.

La réduction du coefficient de frottement par utilisation du bisulfure de molybdène.
Reducing the Friction Coefficient by Using Molybdenum Disulfide.
Pierre Bessière. *Metaux, Corrosion-Industries*, v. 32, Apr. 1957, p. 149-161.
A study of the possible industrial applications of MoS_2 as a lubricant. Effects of speeds, pressure, air, vacuum, and surface phosphatizing treatment.

Antiwear Requirements for Navy Turbine Oils.
H. F. King and J. R. Belt. *Bureau of Ships Journal*, v. 6, July 1957, p. 6-14.

Schmiereigenschaften und technische Anwendung von Graphit und Molybdändisulfid.
Lubricating Properties and Applications of Graphite and Molybdenum Disulfide.
Franz Lihl. *Berg- und Hüttenmännische Monatshefte der Montanistischen Hochschule in Leoben*, v. 102, May 1957, p. 149-154.
Favorable characteristics of graphite and MoS_2 to produce high quality lubricants. Structure and behavior of these lubricants under various working conditions.

2.3. *Processing Lubricants*

Effect of Surface-Active Lubricants Upon Drawing of Metal Wire.
V. D. Chistota, S. Ya Veiler, V.I. Likhtman, and P. A. Rebinder. *Henry Brutcher Translation No.* 3872, 6 p. (From *Doklady Akademii Nauk SSSR*, v. 110, no. 4, 1956, p. 562-565.) Henry Brutcher, Altadena, Calif.
Correlation between number of carbon atoms in the structural chain of lubricants, die pull, and temperature effect (20 to 60°C).

Additives in Steel Mill Lubricants.
M. S. Clark. *Iron and Steel Engineer*, v. 33, Oct. 1956, p. 87-93.
Additives can improve many of the lubricants' properties and also give much longer life to the lubricant. Many factors must be considered, and the use of additive concentrates should always be under laboratory control.

Temperaturmessungen beim Ziehen von Stahldraht. II.
Temperature Measurements in the Drawing of Steel Wire.
Werner Leug and Karl-Heinz Treptow. *Stahl und Eisen*, v. 77, June 27, 1957, p. 859-867.
Effect of lubricants, wire composition, and processing variables on temperature.

Choose With Care Your Press Drawing Lubricants.
Leon Salz. *Tooling and Production*, v. 23, July 1957, p. 87-91.
The need for careful press drawing lubricant selection is emphasized.

Selection of a Lubricant for Cold Drawing. I. Coarse Steel Wire.
Bruce W. Siemon.
II. Fine Steel Wire.
W. B. Bauzenberger. *Iron and Steel Engineer*, v. 33, Nov. 1956, p. 105-108.
Applications of various types of lubricants. Speed and severity of drawing, material, and desired product finish are factors influencing selection.

Anti-Seizing Lubrication for Drawing Steel Items. (in Russian)
S. A. Valiev. *Vestnik Mashinostroeniia*, v. 37, June 1957, p. 38-39.
Requirements and description of a new lubricant based on $Fe(OH)_3$.

2.4. *Bearings*

Bearings for Tough Jobs.
Steel, v. 140, Apr. 8, 1957, p. 114 + 3 pages.
Data on bearing materials for difficult environments, high temperatures, and nuclear reactors.

Load Capacity and Dry Friction Tests of a Water-Lubricated Thrust Bearing.
Stanley Abramovitz. *Franklin Institute Laboratories for Research and Development, Final Report No.* AECU-3150, Feb. 19, 1954 to Aug. 31, 1954, 21 pp. (UF767 U3au Contin.)
Load capacity tests indicated ability to maintain full fluid film under 100 psi. unit load when proper shoe-face curvature was imposed. Dry friction tests resulted in no harmful bearing surface effects during 5-min. period.

Lubrication of Bearings.
F. T. Barwell. 292 pp. 1956. Butterworths Scientific Publications, London. (TJ1075 B28L).
Principles underlying bearing behavior; fundamentals of friction and wear in relation to selection of lubricants and bearing materials; procedure for bearing design.

Grease Lubrication of Rolling Bearings.
J. H. Harris. *Metalworking Production*, v. 101, July 5, 1957, p. 1157-1161.
New development based on Li 12-hydroxystearate. Advantages are outstanding mechanical stability, wide temperature range long shelf-life and resistance to drying-out and hardening in service.

On the Theory of Lubrication in Journal Bearings.
Toshio Nishihara and Yutaka Sugimoto. *Kyoto University, Engineering Research Institute Technical Reports*, v. 6, no. 5, Aug. 1956, p. 75-97.

Analysis of pressure distribution in the oil film of the plain bearing of finite length; viscosity change due to change in temperature or pressure.

Evaluation of Grease Lubricated Bearings at High Rotative Speeds.
J. R. Roach and T. B. Jordan. *Spokesman*, v. 21, May 1957, p. 18-22.
The performance life of grease lubricated bearings decreases with increase in DN value (bore diameter in mm x speed in r.p.m.) and in temperature. The effect of metallic vs. nonmetallic bearing retainers and of outer race-riding vs. inner race-riding retainers on performance life is illustrated.

Air-Lubricated Bearings With Capillary Air-Feeder Holes.
Tokio Sasaki and Haruo Mori. *Kyoto University, Memoirs of the Faculty of Engineering*, v. 19, Apr. 1957, p. 14-24.
Bearings can be operated in quite a stable state and with an extremely small coefficient of friction.

Untersuchungen über die Filmresistenz von Schmierölen im Gleitlager in Abhängigkeit von Belastung und Umdrehungszahl. II. Versuchsdurchführung und Fehlerabschätzung.
Lubricating Oil Film Resistance in Friction Bearing and Its Relation to Load and R.P.M. Investigation of Errors Evaluation.
Ernst Terres, Günter Morlock, and Karl Hans Volker. *Erdöl und Kohle*, v. 9, no. 10, Oct. 1956, p. 690-693.

Small Oil-Free Bearings.
Hobart S. White. *Journal of Research, National Bureau of Standards*, v. 57, Oct. 1956, p. 185-204.
Friction and wear tests on plastics, plastics with fillers, impregnated metals, and impregnated carbon, to determine their suitability for use as oil-free bearings in aircraft clocks and similar instruments between —55 and + 70°C.

Materials for Small, Oil-Free Bearings.
Hobart S. White. *Materials & Methods*, v. 45, Apr. 1957, p. 135-139.
Wear rates and friction coefficients of many combinations of metallic and nonmetallic materials.

3. Deformation and Fracture

Possibility of Determining the Conditions of Breakage According to the Appearance of Fracture Shape. (in Russian)
P. G. Abramov, N. A. Bushe, and N. P. Shchapov. *Zavodskaia Laboratoriia*, v. 23, May 1957, p. 600-601 + 2 plates.
Gives examples of fatigue and impact fractures in Zn alloys at various temperatures.

How to Distinguish Brittle From Tough Steel.
Herman Greenberg. *Metal Progress*, v. 71, June, 1957, p. 75-81.
To insure freedom from brittle failure in service, steel should have a "nil-ductility transition (NDT) temperature" below its minimum working temperature. At temperatures below NDT, samples with a sharp notch break with all-cleavage fracture.

The Relation During Creep Between Grain-Boundary Sliding, Sub-Crystal Size, and Extension.
D. McLean and M. H. Farmer. *Institute of Metals, Journal*, v. 85, Oct. 1956, p. 41-50.
Grain-boundary sliding was found to be approximately proportional to elongation, a slight deviation occurring in the case of Cu. Relationship with sub-crystal diameter was not confirmed.

Dislocation Locking and Fracture in α-Iron.
J. Heslop and N. J. Petch. *Philosophical Magazine*, v. 2, ser. 8, May 1957, p. 649-658.
Inhibition of plastic deformation by dislocation locking promotes brittleness. Ductility conferred by Mg in the Fe is associated with weakened dislocation locking as well as with grain refinement. The weakening of the locking appears to be due to interaction between N and Mn atoms.

Recherches sur la broyabilité de la matière.
Research on the Crushability of Materials.
Michel Papadakis. *Revue des Matériaux de Construction*, C. no. 500, May 1957, p. 131-139.
The crushability of a material, free from impurities, is independent of fineness, and may be defined by a single number. Heterogeneous bodies offer several successive crushabilities, depending on the fineness required.

Effects of Solid Environments on the Brittle Fracture of Zinc Single Crystals.
L. C. Weiner and M. Gensamer. *Institute of Metals, Journal*, v. 85, June 1957, p. 441-448 + 1 plate.
The normal fracture stress of crystal oriented with $X_o = 3°$, tested in tension at room temperature, is increased 43% upon applying a surface film of Cu, Au, ZnO, Sn, or Zn thicker than 500 A. Above this value the increase is independent of film thickness. The primary mode of deformation is twinning accompanied by parent basal slip both before and after twinning, as well as basal slip within the twins. The fracture stress of coated crystals oriented with $X_o = 83°$ is 48% less than the value observed with clean-surfaced crystals.

4. Wear

4.1. *General and Fundamentals*

Fundamentals of Wear.
Lubrication, v. 42, Dec. 1956. p. 149-160.
Reviews the basic knowledge which has been developed in this field and discusses how it may be applied to the understanding of problems in lubrication, particularly of metal surfaces and liquid lubricants.

Why Materials Wear.
Verne Pulsifer. *Frontier*, v. 19, Winter 1956, p. 8-11.
Types of wear and their occurrence; wear resistant structures.

Atomic Capture From Solids in Friction. (in Russian)
D. N. Garkunov and I. V. Kragel'skii. *Doklady Akademii Nauk SSSR*, v. 113, no. 2, Mar. 11, 1957, p. 326-327.
Selective diffusion of atoms and particles from an alloy during friction.

Meteoric Dust Erosion Problem and Its Effect on the Earth Satellite.
Stuart A. Hoenig. *Aeronautical Engineering Review*, v. 16, July 1957, p. 37-40.
Indicates that for short-lived vehicles the hazard is negligible.

Wear in High Speed Diesel Engines Operating on Power Alcohol as Principal Fuel.
M. R. K. Rao and Y. M. Balakrishna. *Indian Institute of Science, Journal*, v. 39, sec. B, Jan. 1957, p. 17-22 + 3 plates.
Prolonged operation of a diesel engine with neat alcohol as the principal fuel has no adverse effect on the rate of wear. There is a noticeable reduction of engine deposits.

The Influence of Dust Particles on the Contact of Solids.
J. B. P. Williamson, J. H. Greenwood, and J. Harris. *Royal Society, Proceedings*, v. 237, ser. A, Nov. 20, 1956, p. 560-573.
The various possible methods of increasing the probability that direct contact will occur. General relations by means of which the behavior of two contacting solids under any given concentration of dust may be predicted.

4.2. *Types of Wear*

Fretting Corrosion and Its Influence on Fatigue Failure.
A. J. Fenner, K. H. R. Wright, and J. Y. Mann. Paper from "International Conference on Fatigue of Metals". v. II. Institution of Mechanical Engineers. 10 p. + 4 plates. (TA460 In8p Over.)
Characteristics and mechanism of fretting; the fretting behavior of non-ferrous surfaces; fretting corrosion and service failures.

Korrosion, Rissbildung und Erosion an der Aussenfläche von Kondensator-rohren aus Kupferlegierungen. II.
Corrosion, Cracking and Erosion on the Outer Surface of Copper-Alloy Condenser Tubing.
F. W. Nothing. *Metall*, v. 10, nos. 21-22, Nov. 1956, p. 1033-1038.
Stress corrosion; cracking and corrosion. Corrosion fatigue and erosion.

Investigation of Erosion-Corrosion Phenomena Caused by Neutral Salt Solutions Carrying Solid Suspensions. (in Polish)
M. Śmialowski and J. Siejka. *Przemysl Chemiczny*, v. 12, no. 10, Oct. 1956, p. 569-571.
Loss in weight of two types of steel (T-45 steel of 0.10% Cr content and TR-2 steel of 1.14% Cr) was compared after rotating in solutions of NaCl containing suspended sand or SiC.

Fretting Corrosion.
R. B. Waterhouse. *Institution of Mechanical Engineers, Proceedings*, v. 169, no. 59, 1955, p. 1157-1172.
Characteristics; effect of various factors on amount of damage; possible mechanisms; preventive measures.

4.3. *Metals*

Preliminary Metallographic Studies of Ball Fatigue Under Rolling-Contact Conditions.
H. Robert Bear and Robert H. Butler. *U.S. National Advisory Committee for Aeronautics, Technical Note* 3925, Mar. 1957, 38 pp. (TL 570 Un3t).
Origin and progression of fatigue failures were observed at room temperature and 200 to 250°F.

Friction, Wear, and Surface Damage of Metals as Affected by Solid Surface Films.
Edmond E. Bisson, Robert L. Johnson, Max A. Swikert, and Douglas Godfrey. *U.S. National Advisory Committee for Aeronautics, Report* 1254, 1956, 19 pp. (TL 521 Un3r Vis.)
Friction and surface damage of metal are reduced by solid surface films such as graphitic C, NiO, FeO, Fe_3O_4, FeS, $FeCl_2$, and MoS_2.

The Size Effect in Studying Friction and Wear in Metals.
V. I. Bondar'. *Fizika Metallov i Metallovedenie* v. 3, no. 2, 1956, p. 363-368.
A study of factors to be considered when making wear and friction tests. Effects of changing shape and size of specimens on the results obtained.

Transition Temperature for Surface Damage in Sliding Metallic Contact.
L. F. Coffin, Jr. *Lubrication Engineering*, v. 13, July 1957, p. 399-405.
Effect of both liquid atmosphere and temperature on alloying couples, particularly Cu-Cu, Cu-Ni, and Ni-Ni under repetitive sliding. Effect of speed of sliding, load, kind of fluid, and kind of metal on the transition temperature.

Wear Produced by Mutual Rubbing of Similar Metals. (in Russian)
V. N. Kashcheev. *Fizika Metallov i Metallovedenie*, v. 3, no. 2, 1956, p. 369-373.
The body which reaches the higher temperature during the application of friction wears more slowly. The process is characterized by binding and the formation of a roughened surface.

The Connection Between Hardness Under Compression and Hardness During Abrasion in Metals and Minerals. (in Russian)
M. M. Krushchov and M. A. Babichev. *Zavodskaia Laboratoriia*, v. 23, no. 2, 1957, p. 224-228.
Concludes that there is a regular relationship between relative resistance to wear and hardness under compression.

Investigations on the Transition Resistance of Copper and Silver Contacts. (in Hungarian)
József Mocsáry. *Elektrotechnika*, v. 49, no. 9, Sept. 1956, p. 275-280.
Relation of contact pressure and resistance; effects of mechanical vibration.

Resistance of Metals to Scoring. (in Russian)
A. V. Ratner. *Teploenergetika*, v. 4, May 1957, p. 30-35.
Results of tests on several materials as to their resistance to scratching. The reasons for this wear are analyzed. A relationship is determined between the relative increase in surface hardness and the resistance of materials to scoring.

4.3.1. *Ferrous Metals*

Effect of Alternate Corrosion and Abrasion on Some Ferrous Metals.
J. Dearden and J. D. Swindale. *Iron and Steel Institute, Journal*, v. 185, Feb. 1957, p. 227-234.
Resistance to corrosion was reduced by abrading the rust, and increasing frequency of abrasion increased the corrosion rate, except for gray cast iron. Resistance to abrasion alone was found to be related to a defined equivalent carbon content of the steels tested rather than to their hardness. Three white cast irons showed exceptional resistance to corrosion, even when combined with abrasion and to abrasion alone.

Wearability of Steel and Residual Stresses in Surface Layers. (in Russian)
D. A. Draigor and V. A. Shevchuk. *Akademiia Nauk Ukrains'koi RSR, Dopovidi*, no. 5, 1956, p. 430-433.
Distribution of stresses; tension effects on wearability; optimal tensile strength.

The Nature of Mechanically Polished Metal Surfaces. Deformation Produced During Abrasion of 18/8 Type Austenitic Steel.
L. E. Samuels and G. R. Wallwork. *Iron and Steel Institute, Journal*, v. 186, June 1957, p. 211-218.
The structure of the deformed surface layer produced during the abrasion was investigated by a metallographic taper-sectioning technique. Requirements of mechanical methods of polishing necessary for the production surfaces free from gross deformation are considered.

Reducing the Tendency of Lubricated Stainless Steel to Sieze Under Friction. (in Russian)
B. Kh. Somin and S. L. Matskevich. *Vestnik Mashinostroeniia*, v. 37, Mar. 1957, p. 28-34.
Causes of seizing: effects of alloying elements; suggested surface treatments.

Studying the Wear Resistance of Steel Subjected to Abrasion. (in Russian)
M. M. Tenenbaum and V. M. Guterman. *Vestnik Mashinostroeniia*, v. 36, Dec. 1956, p. 25-29.
Effects of sliding on the wear of specimens of various hardnesses. Influence of various depths of case-hardening.

4.4. *Machine Parts and Machines*

Protection of Refractories by Moving Air Curtains.
J. H. Clesters. C. Holden, and A. D. Robertson. *Iron and Steel Institute, Journal*, v. 185, Feb. 1957, p. 177-200.
Tests suggest that relatively slow moving air curtains in open-hearth furnaces emerging from an essentially continuous slot afford sufficient protection to the refractories to warrant their trial in areas where excessive wear is normally experienced.

Some Considerations of Wear in Marine Gearing.
W. H. Darlington. *Institute of Marine Engineers, Transactions*, v. 58, Sept. 1956, p. 289-308.
Design, manufacture, and operation of three sets of marine double reduction gears.

Tire Wear and Fuel Consumption.
H. C. J. de Decker, G. J. Van Amerongen, and J. F. Benders. *Rubber Chemistry and Technology*, v. 29, Oct.-Dec. 1956, p. 1445-1457. (From *Kautschuk und Gummi*, v. 8, Sept. 1955, p. 21-26.)
Measurements show that GR-S tires are advantageous only in a tropical climate. In all other countries natural-rubber tires are more economical.

Temperature Affects Engine Valve Wear.
Max J. Tauschek. *SAE Journal*, v. 65, July 1957, p. 53-54.
The characteristic heat pattern and its control.

5. Analysis and Testing

5.1. *Surface Structures*

Images d'échantillons métalliques contraints obtenues au microscope à photoémission.
Images of Strained Metal Samples, Obtained With the Photoemission Microscope.
R. Bernard, C. Guillaud, and R. Goutte. *Journal de Physique et le Radium*, v. 18, May 1957, p. 327-330.
Studies with Au samples show an increased brightness in areas of maximum strain (breaking zone), probably due to a local increase of the photoelectric emission factor.

Identification of Minute Amounts of Metals and Alloys by Electrosolution and Electrophoresis.
Charlotte L. Brown and Paul L. Kirk. *Mikrochimica Acta*, 1956, no. 11, p. 1593-1599.
A scheme for extraction on the surface of metals and alloys of minute amounts of material in a state suitable for direct electrophoretic separation and analysis.

X-Ray Study of the Quality of Metal Surfaces Prepared by Rapid Machining.
(in Russian)
T. Kh. Chormonov. *Izestiia Akademii Nauk SSSR, Seriia Fizicheskaia*, v. 20, no. 6, June 1956, p. 703-705.
Relation of depth of propagation of plastic deformations in steel and brass to rate of machining and feed; distortions of second and third order.

Chemical Analysis of Surface Layers of Metals Exposed to Various Types of Wear.
(in Russian)
B. I. Kostetskii, N. L. Golego, and P. K. Topekha. *Vestnik Mashinostroeniia*, v.36, no. 10, Oct. 1956, p. 25-26.
The role of O in the hard, white surface formations of steel exposed to certain friction conditions.

How to Reveal the Microstructure of Non-Etching Surface Layers on Ferrous Metals.
B. A. Krasyuk. *Henry Brutcher Translation No.* 3920, 6 pp. (From *Zavodskaia Laboratoriia*, v. 22, no. 5, 1956, p. 556-558.) Henry Brutcher. Altadena, Calif.
A study of failure of known etchants to bring out the structure of surface layers of ferrous metal which have been subjected to surface treatment.

Analyzing the Textures of Rolled Aluminum. (in Spanish)
Jose Terraza Martorell and Juliana Arroyo Ruiperez. *Instituto del Hierro y del Acero*, v. 10, Jan.-Mar. 1957, p. 20-35.
A photometric study of rolled Al diffractograms by means of different microphotometers. Textures for various degrees of reduction. Variation of the polar figures.

The Nature of Mechanically Polished Metal Surfaces: The Surface Deformation Produced by the Abrasion and Polishing of 70: 30 Brass.
L. E. Samuels. *Institute of Metals, Journal*, v. 85, Oct. 1956, p. 51-62 + 4 plates.
Certain principles are established for methods by which surfaces free from serious strains may be produced by mechanical methods of polishing. Structure suggests that fine metallographic polishing operations occur essentially by a cutting mechanism.

X-Ray Study of the Quality of the Surface on Finely Ground and Machined Metals.
(in Russian)
Iu. S. Terminasov, A. G. Iakhontov, and A. V. Poltavskii. *Izvestiia Akademii Nauk SSSR, Seriia Fizicheskaia*, v. 20, no. 6, June 1956, p. 689-692.
Parallels in structural changes and microhardness between a finely-machined surface and the surface produced by grinding-polishing. Dislocations and distortions in lattice and reduction in size and deformation.

Absolute Areas of Some Metallic Surfaces.
Thomas L. O'Connor and Herbert H. Uhlig. *Journal of Physical Chemistry*, v. 61, Apr. 1957, p. 402-405.
Roughness factors were calculated for abraded iron foil and 18-8 stainless steel under various circumstances with ethane as adsorbate at —183°C.

5.2. *Hardness*

Erfahrungen mit Risstiefenmessern.
Apparatus for Measuring the Depth of Cracks. Lutz Brand. *Stahl und Eisen*, v. 77, May 2, 1957, p. 576-581.
Calibration curves of apparatus for determination of the depth of cracks at the surface of metals with the use of direct or alternate current. Variables influencing the scatter range of the curves. Comparison of measured results with true depths.

Testing Indentation and Abrasive Hardness of Hard Materials.
P. Grodzinski. *Industrial Diamond Review*, v. 17, Jan. 1957, p. 7-14.
Phenomonologic and rheologic considerations. Hardness data on various materials; testing apparatus. (To be continued.)

Hardness and Its Measurement.
Vincent E. Lysaght. *Metal Treating*, v. 8, May-June 1957, p. 2 + 12 pages.
Significance of hardness testing; instruments and techniques; testing hardness of tempered steel, case-hardened steel, cast iron, and nitrided and thin case-hardened surfaces.

The Accurate Measurement of Wear Scars on Cutting Tools.
J. Taylor. *Machinery (London)*, v. 90, Apr. 26, 1957, p. 927-934.
Modifications required for improving the accuracy of wear measurements by microscopes. The wear scar planimeter and its use for plotting tool wear curves.

5.3. *Tracer Techniques*

Radioisotope in Metallurgie und Metallkunde.
Radioactive Isotopes in Metallurgy and Metallography.
Traude Bernert. *Berg- und Hüttenmännische Monatshefte der Montanistischen Hochschule in Leoben*, v. 101, no. 11, Nov. 1956, p. 213-219.
Uses of radioactive isotopes in studies of diffusion, microstructure, wear and abrasion, Al casting, and routine tests.

Metallic Transfer in Engineering Operations. Radioactive Methods Used at Cambridge.
F. P. Bowden and J. B. P. Williamson. *Engineering*, v. 182, Nov. 16, 1956, p. 619-621.
Whenever a metal is manipulated mechanically, small fragments of the tools used become torn out and embedded permanently in its surface. This form of contamination can have a profound effect on the subsequent behavior of the metal.

Radioactive Wear Measurements, an Approach to Rapid Routine Testing for Tool Performance.
O. Hake. *Henry Brutcher Translation No. 3584*, 8 p. (From *Industrie Anzeiger*, v. 77, no. 45, 1955, p. 627-630.) Henry Brutcher, Altadena, Calif.
A method based on γ-ray measurements of the quantity of activated tool material taken away by the chips in machining operations. Data on machining a semi-hard C steel with tools tipped with five different cemented carbide compositions and a high-speed tool steel.

Material Loss in Francis Turbines Through Cavitation. (in Norwegian)
Kjell Rosenberg. *Teknisk Ukeblad*, v. 103, no. 38, Oct. 18, 1956, p. 859-862.
The material loss caused by cavitation on the moving wheel was measured by means of radioactive isotopes. More economical turbine operation is possible.

Measuring the Wear of Machine Parts With Radioactive Isotopes. (in Czech.)
L. Šimon. *Strojírenství*, v. 7, Jan. 1957, p. 41-48.
Measuring procedure; selection of suitable isotopes, their activation, and introduction into the parts.

Use of Radioactive Tracers in the Investigation of Wear of Drop-Forging Dies. A Preliminary Investigation.
D. B. Smith, H. Southan, and H. A. Whiteley. *Metal Treatment and Drop Forging*, v. 24, Apr. 1957, p. 131-136.
Method can give reasonably accurate measurements of the rate of die wear but its main use seems to be in assessing the various factors involved in die wear and in explaining its mechanism.

5.4. *Wear Testers*

Surface and Subsurface Abrasion Tests for Porcelain Enamels.
James H. Giles, Jr. and J. C. Richmond. *American Ceramic Society, Bulletin*, v. 36, June 1957, p. 205-207.
Enameled metal specimens are abraded for a designated time with a charge of abrasive, stainless steel balls, and water. The percentage of initial gloss retained is taken as the index of resistance to surface abrasion, and the inverse rate of weight loss is taken as the index of resistance to subsurface abrasion.

Cam & Tappet Test for Lubricants. II. Wear Evaluation.
E. H. Loeser, S. B. Twiss, and D. M. Teague. *Lubrication Engineering*, v. 13, May 1957, p. 269-274.
A lubricant tester, designed for the study of metal scuff under combined sliding and rolling contact with cyclic variation of load, can be used to evaluate wear before the scuffing occurs. The wear of cast-iron cams

is decreased several fold by the addition to the oil of 0.75% of an anti-scuff additive, zinc dialkyl dithio-phosphate.

A Device for Testing the Wear Resistance of Surface Coatings.
Jack McCarthy and James Morgia. *Plating*, v. 43, Oct. 1956, p. 1248-1250.
Description of rotobrader mechanism.

Wear Tests With the Accelerator.
A. R. Macormac and F. M. Richardson. *American Dyestuff Reporter*, v. 46, Feb. 25, 1957, p. 149-151.
Percentage of worn wool ends consistently increased with increased time in the Accelerator, indicating a good method for measuring the abrasive damage to wool fabrics in this machine.

6. Wear Resistance of Materials

6.1. *Metals*

Symposium on Metallic Materials for Service at Temperatures Above 1600°F.
193 pp. 1956. American Society for Testing Materials, Philadelphia. (TA460 Am 35sm)
Fourteen papers on properties of such materials as TiC, nimonic alloy, Co alloys, Zr-rich protective coatings, and Inconel and Cr-Ni alloys.

Selection of Hard Facing Materials for Lowest Maintenance Cost.
N. D. Berrick. *Australasian Engineer*, v. 48, Aug. 1956, p. 47-53.
Structure and properties of materials. Types of hard facing rods and electrodes. Service performance of hard faced parts.

Handbuch der Sonderstahlkunde.
(in German) Handbook of Special Steel Metallography.
Eduard Houdremont. 3rd Rev. Ed. v. II. 1538 pp. 1956. Springer-Verlag, Berlin. (TN756 H81h3)
Structure and properties of steels containing W, Mo, V, Co, Si, Al, Cu, O, N, H, P, S, Ti, Cb, Ta, B, and rare metals.

Nitrided Chromium for Wear Applications.
S. W. McGee and C. H. Sump. *ASTM Bulletin*, 1956, no. 217, Oct. 1956, p. 58-62.
The treated metal had the most satisfactory wear resistance of a variety of materials tested for service in oxygenated water at 500 F.

"Kanigen" Chemical Nickel Plating.
G. Gutzeit and E. T. Mapp. *Corrosion Technology*, v. 3, Oct. 1956, p. 331-336.
Method for uniformly coating metals and non-metals with a layer of hard, corrosion-resistant amorphous Ni-P alloy. Non-porous coating is hard but relatively brittle, adheres well to most properly pretreated basis materials.

Steel Castings Shrug Off Wear and Impact Abuse.
C. G. Mickelson. *Iron Age*, v. 179, Feb. 21, 1957, p. 100-101.
"Wearpact" steel wears out slowly and evenly, is magnetic, can be welded by conventional arc techniques, and can be machined with carbide tooling.

Materials Engineering File Facts. Cobalt and Cobalt Alloys.
F. R. Morall. *Materials & Methods*, v. 44, Oct. 1956, p. 141.
Materials data sheet includes composition, physical and mechanical properties, thermal treatment, fabricating properties, and corrosion resistance.

How to Select Chrome-Moly Steels for Ball and Rod Mill Liners.
T. E. Norman. *Engineering and Mining Journal*, v. 158, July 1957, p. 102-106.
The properties, fields of application, and comparative wear resistance of "Chrome-Moly" liner steels.

La trempe par induction comme moyen d'augmenter la résistance à l'usure dans les moteurs thermiques et les machines.
Induction Tempering for More Wear Resistance in Heat Engines and Machines.
G. W. Seulen. *Métallurgie et la Construction Mécanique*, v. 88, no. 10, Oct. 1956, p. 823 + 6 pages.
Principles and effects of induction tempering; properties of steels suitable for tempering.

Tool Steels. II. Why Do Tool Steels Fail?
L. F. Spencer. *Steel Processing and Conversion*, v. 43, June 1957, p. 315 + 9 pages.
An investigation of failures caused by design, poor quality steel, heat treatment, and operational procedures.

Wear Resistance of Carbon- and High-Chromium Steels. (in Russian)
D. Ia. Vishniakov and A. G. Vinitskii. *Metallovedenie i Obrabotka Metallov*, no. 4, Apr. 1957, p. 2-9.
Wear intensity depends on the composition and structure of the steel. An increase in quantity of carbides results in increased wear resistance.

6.2. *Bearing Materials*

Special Materials for Unusual Ball-Bearing Applications.
William Blinder. *General Motors Engineering Journal*, v. 4, Jan.-Mar. 1957, p. 42-46.
Material evaluation methods; high-temperature, non-magnetic, and corrosion-resistant applications; principal properties of ball-bearing and separator materials.

Aluminum-Tin Bearings. High Tin Types Reduce Wear.
E. C. Ellwood. *Materials & Methods*, v. 45, June 1957, p. 110-113.
With as-cast brittleness eliminated by heat treatment, Al bearings containing 25 to 50% Sn offer low wear and good fatigue resistance. They are particularly useful for heavy loads on unhardened steel shafts.

Frictional Characteristics and Surface Damage of Thirty-Nine Different Elemental Metals in Sliding Contact With Iron.
C. L. Goodzeit, R. P. Hunnicutt, and A. E. Roach. *ASME, Transactions*, v. 78, Nov. 1956, p. 1669-1676.
Surface-damage characteristics are related to the relative hardness of the metals in sliding contact, their mutual solubility, and their ability to form intermetallic compounds.

Wear Properties of 60 : 40 Brass Containing Lead.
Fusao Hayama. *Castings Research Laboratory, Report, Waseda University*, 1956, no. 7, p. 81-82.
Variation of wear rate with speed, pressure, and lead content.

Development of Friction-Seal Materials for High Temperature-High Speed Operation.
Peter F. Mataich. *Wright Air Development Center Materials Laboratory, WADC Technical Report* 56-579, Feb. 1957, 18 p. (TL 507 Un3.18w Vis.)
The 30 Ni- and Co-base alloys evaluated showed excessive wear which was attributed to the excessive temperatures reached at the mating surfaces when the lubricating oil film broke down. This condition could be remedied by incorporating a suitable solid lubricant in the seal material itself.

Aluminum-Lead Bronze Bearing Metal.
(in Russian)
E. F. Merkulov. *Tsvetnye Metally*, v. 30, June 1957, p. 67-69.
Replacement of high-lead bronzes with one containing 7-11% Sn. Successful use in tractor engines.

Scoring Characteristics of Thirty-Eight Different Elemental Metals in High-Speed Sliding Contact With Steel.
A. E. Roach, C. L. Goodzeit, and R. P. Hunnicutt. *ASME, Transactions*, v. 78, Nov. 1956, p. 1659-1667.

A New Oil-Less Bearing Material.
John D. Shaw and Walter V. Knopp. *Product Engineering*, v. 28, Jan. 1957. p. 203-205.
Characteristics and properties, advantages and limitations of full density graphite-metal powder combinations, self-lubricating even at extreme temperatures and pressures.

6.3. *Organic Materials*

Neue Erkenntnisse über Gleiteigenschaften von Polyamiden. I.
New Ideas on the Frictional Properties of Polyamides.
H. R. Jacobi. *Kunststoffe*, v. 47, May 1957, p. 234-239.
With the Almen-Wieland apparatus, curves are obtained which help to assess the effect of adding graphite and MoS_2 under various working conditions and with different combinations of the two materials. Increased knowledge of the morphological relationship led to the preparation of polyamides having a regular structure and extremely fine grain.

Stability of Nylon Parts in Business Machines.
Byron W. Nelson. *SPE Journal*, v. 13, Feb. 1957, p. 13-16, 64.
Wear of nylon in contact with other materials; surface finish requirements for mating steel parts in moving contact with nylon; effect of relative humidity on dimensions of nylon parts.

Einfluss des Weichmacheranteils bei PVC-Fördergurten.
The Effect of Plasticizers on PVC Conveyor Belts.
Bernd Passmann. *Kautschuk und Gummi*, v. 10, June 1957, p. 135-136.
Inflammability, flexibility, resistance to abrasion, maximum load, and electrical resistance of belt with varying plasticizer contents, with and without antistatic agents.

Neuere Ergebnisse der Kautschuk-Physik.
Recent Developments in the Physics of Rubber.
A. Schallamach. *Kautschuk und Gummi*, v. 10, June 1957, p. WT135-WT140.
Elasticity, resistance to tearing and to abrasion of various filled and unfilled natural rubber vulcanizates.

6.4. *Inorganic Materials*

Sintered Metal Oxides-New Tool Material.
(in Czech.)
Witold Biernawski. *Strojírenská Výroba*, v. 5, June 1957, p. 42-245.
Manufacturing technique and tests of sintered metal oxide. Use of ultraviolet rays in

testing. Material can be used for cutting light and non-ferrous metals, alloys, and steel, provided cutting is uninterrupted. Material can replace 10 to 15% of costly sintered carbides.

Improvement of the Impact Resistance of Cermets.
A. C. Pezzi and H. P. Kling. *Wright Air Development Center, Materials Laboratory, WADC Technical Report* 56-329, *Apr.* 1957, 27 pp. (TL507 Un3.18w Vis.)
Application to K161B bars of 0.018 in. of electrodeposited Ni, bonded by a suitable vacuum heat treatment, raised the impact strength from values of 2.56 and 3.36 in.-lbs. at room temperature and 1800°F respectively to values of 21.48 and 18.96 in.-lbs. at the same temperatures.

The Relation Between Modulus of Elasticity and Abrasion Resistance in Refractory Materials.
C. Storey and J. Mackenzie. *British Ceramic Society, Transactions*, v. 56, Jan. 1957, p. 14-21.

Refractory Linings of Rotary Furnaces for Bloomery Process. (in Czech.)
Eugen Viktora and Vaclav Zavesky. *Hutnicke Listy*, v. 12, May 1957, p. 417-423.
Completely sintered materials give the greatest durability. Directions on how to increase service life of linings.

Nitride-Bonded Silicon Carbide Bridges Gap Between Metals and Ceramics.
W. L. Wroten. *Product Engineering*, v. 28, Feb. 1957, p. 135-139.
Shape and size factors, surface characteristics properties at elevated temperatures; application and cost data; heat, abrasion, and corrosion resistance.

6.5. *Abrasives*

Abrasives and Wear.
Lubrication, v. 43, Feb. 1957, p. 13-24.
Bearing design; bearing damage; abrasive materials and their effects; elimination of abrasives from oil systems.

New Techniques in Coated Abrasive Machining Methods.
Hugh N. Dyer. *Tooling and Production*, v. 22, Jan. 1957, p. 63-68.
Variables affecting the belt grinding process and their control. Includes backing support, abrasives, and grinding fluids.

Hydraulic Abrasive Blasting of Metal Parts. (in Russian)
N. G. Markov, F. V. Kisliakov, and M. M. Trukhachev. *Vestnik Mashinostroeniia*, v. 36, no. 9, Sept. 1956, p. 56-57.
Describes a machine designed for treating metallic surfaces with liquids carrying an abrasive material. The treatment is claimed to be free from the usual defects of other machining methods, and to improve the fatigue strength and corrosion resistance of the part treated.

The Uses of Diamond Abrasives in Metallographic Polishing.
L. E. Samuels. *Industrial Diamond Review*, v. 16, Dec. 1956, p. 233-237.
Relief between constituents and preservation of edges; retention of non-metallic inclusions and constituents; polishing special materials.

An Analytical Study on Grinding Resistance.
Kenji Sato. *Technology Reports, Tôhoku University*, v. 21, no. 1, 1956, p. 147-177.
Magnitude and direction of force acting on a single grain; scratch test by single grain; formula for grinding resistance; measuring devices; experimental data.

Preparation for Electroplating With Coated Abrasives.
Warren K. Seward. *Plating*, v. 44, Jan. 1957, p. 43-46.
Role of contact wheel; belt speed; selection, handling, and storage of abrasives; lubricants; some operating techniques.

How to Select and Use Contact Wheels.
Warren K. Seward. *Products Finishing*, v. 21, July 1957, p. 24-35.
Discusses contact wheels for abrasive belt polishing from the standpoint of application; proper techniques for economical operation.

Coated Abrasives in Metal Finishing.
J. Zoethout. *Product Finishing*, v. 10, July 1957, p. 53 + 6 pages.
Applications of backstand machines; types of abrasive belts available; contact wheels.

7. Surfaces and Surface Treatment

7.1. *General*

Steam Atmosphere Heat Treatment.
Canadian Metalworking, v. 20, June 1957, p. 50-52.
Heat treatment with the use of steam atmosphere and electric heat can provide advantages such as improved wear resistance, longer life, better machinability, and greater corrosion resistance. Typical applications in both ferrous and non-ferrous fields are discussed.

Hard Coatings and Surfaces for Metals.
Robert J. Fabian. *Materials & Methods*, v. 45, Jan. 1957, p. 121-140.
Survey of the major types of hard coatings and surfaces. What metals can be treated; hardness and thickness; wear and corrosion properties; chief advantages and limitations.

Über die bleibende Härte galvanischer Silberniederschläge.
Hardness of Silver Electrodeposits. J. Fischer. *Metall*, v. 11, June 1957, p. 485-490.
Study of the factors which increase or decrease the hardness of Ag plate.

Zur Frage der Glanzeloxierung des Aluminiums.
Anodic Treatment of Aluminum. W. Helling and H. Neunzig. *Metall*, v. 11, June 1957, p. 490-498.
Alteration of Al surface by chemical and anodic polishing as well as by mechanical methods.

Developments in Sprayed Metal Coatings.
Herbert S. Ingham. *Metalworking Production*, v. 100, Sept. 21, 1956, p. 1521-1525.
Advances in the design of powder spray guns now permit economical spraying of metal alloys and ceramic materials. Available spray guns are compared; fusing and other properties of the alloys are discussed.

Le durcissement superficiel par induction haute fréquence, et son application à l'échelle européenne.
Surface Hardening by High-Frequency Induction and Application in European Industry.
M. Labrousse. *Métallurgie et la Construction Mécanique*, v. 88, no. 9, Sept. 1956, p. 725-726, 729-731.
Technique; surface structure changes. Use on a production line basis. Comparison of contour hardening in the U.S.A. and France.

Amélioration de la résistance à l'oxydation et à l'usure au moyen d'un dépôt non galvanique de nickel.
Improving Oxidation and Wear Resistance Through Non-Electrolytic Deposition of Nickel.
A. Portalupi and E. Melgara. *Métallurgie et la Construction Mécanique*, v. 88, no. 9, Sept. 1956, p. 747-749, 751, 753.
Chemical Ni plating compared to the electrolytic process. Better protection of edges by chemical coating.

Some Properties of Oxide Layers Produced on Aluminium by Electrolytic Oxidation.
W. Ch. van Geel and B. J. J. Schelen. *Philips Research Reports*, v. 12, June 1957, p. 240-248.
Thickness, dielectric constant, and density measurements. Layer of mainly amorphous Al_2O_3, made up of O atoms arranged in a closed-packed lattice, which is often, but need not necessarily be, cubic.

The Hard Surfacing of Wear-Resistant Metal Surfaces. (in Dutch)
P. G. Weeber, J. W. Mey, and Th. Berkhout. *Smit Mededelingen*, v. 11, no. 3, July-Sept. 1956, p. 69-77.
Preferred type of hard surfacing metal, method of application, and the measurement of wear resistance.

Preparation of Protective Coatings by Electrophoretic Methods.
Allen C. Werner, James J. Shyne, Harold N. Barr, and Bernard Triffleman. *Wright Air Development Center, Materials Laboratory, WADC Technical Report* 56-521, Apr. 1957, 46 p. (TL507 Un3.18w Vis.)
Studies on protection of Mo and graphite. Multilayer coatings of 80% Ni-20% Cr and Ni-bonded Cr_3C_2 provided good static air-oxidation resistance. Inclusions of a 50% dense Ni-Cr layer resulted in satisfactory ballistic impact resistance. Erosion was fair.

Cleaning Metals and Alloys.
C. B. F. Young. *Metal Finishing*, v. 54, Oct. 1956, p. 57-60, 65.
Surface contaminants, polishing and buffing compounds; ultrasonic cleaning; removal of surface films. (To be continued.)

7.2. Steel

Practical Aspects and Methods of Carbon Control in Heat Treatment.
Wilson T. Groves. *Industrial Heating*, v. 23, Oct. 1956, p. 2060 + 10 pages.
Effect of surface C concentration on wear and fatigue life; control of concentration.

Chromizing for Resistance to Corrosion and Wear.
Daniel E. Lehane and Richard L. Wachtell. *Product Engineering*, v. 27, Nov. 1956, p. 180-183.
How gaseous diffusion of Cr produces either ductile or hard surfaces on steel parts. Influence of base metal on the characteristics of the case.

Wear Protection of Mild Steel by Phosphating.
J. W. Midgley. *Iron and Steel Institute, Journal*, v. 185, Feb. 1957, p. 215-224.
A microscopic study of the change in the nature of mild-steel surfaces phosphated in an accelerated Fe phosphate, or an accelerated Fe-Mn phosphate bath, and of the changes during subsequent wear tests.

Sulfidizing (of Steel and Cast Iron) in Fused Salts.
E. M. Morozova and F. R. Florensova. *Henry Brutcher Translation No.* 3839, 10 pp. (Abridged from *Stanki i Instrument*, v. 27, no. 5, 1956, p. 27-30.) Henry Brutcher, Altadena, Calif.
Influence of S impregnation on hardness, wear resistance, and coefficient of friction. Advantages of sulfidizing machine parts.

Nitriding of Structural Steels. (in Russian)
E. M. Morozova and A. P. Skuzovatova. *Stanki i Instrument*, v. 27, no. 9, Sept. 1956, p. 25-27.
Experimental nitriding of steels alloyed with Cr, Cr and Si, and Cr and Zr. Nitriding increases surface hardness and wear resistance.

Das Nitrieren von Eisenlegierungen und seine Auswirkung auf den Verschleisswiderstand.
Nitriding of Iron Alloys and Its Effects on Wear Resistance.
Johannes Müller. *Härterei-Technische Mitteilungen*, v. 9, no. 3, 1955, p. 25-44.
Various nitrided specimens were tested with a surface endurance testing machine and the effects of hardness and of N on wear were examined. Nitriding of steels and cast iron; application in various fields.

The Nature of the Polished Layer at the Friction Surface of Steel. (in Russian)
N. N. Seleznev, I. E. Brainin, and P. I. Kuleshov. *Vestnik Mashinostroeniia*, v. 37, Mar. 1957, p. 35-39.
Nature of transformations taking place at the surface layer of rubbing steel parts. The polished zone consists of martensite, residual austenite, and alloyed cementite.

7.3. *Grinding*

Behavior of Grinding Wheels. (in Spanish)
Tecnica Metalurgica, v. 13. Mar.-Apr. 1957, p. 81-86.
Hardness of grinding wheels was studied as a function of the quality and grain size of the abrasive. Effect of wheel characteristics on work performed. Criteria for selection of wheels for a particular job.

Continuous-Dress Grinding.
Anderson Ashburn. *Metalworking Production*, v. 101, June 28, 1957, p. 1106-1108.
Key to process is a form cutter for grinding wheels containing cemented diamond particles in a powder-metal body. The cutter is used in a set-up to provide continuous or cycle dressing to provide "perpetual form control".

Ball Mills and Ball Milling. I.
T. G. Callcott. *British Coal Utilisation Research Association, Monthly Bulletin*, v. 21, May 1957, p. 101-120.
Description and performance of mills; grinding circuits; power requirements; wear of grinding media. (To be concluded.)

Grinding Ball Rationing.
Walter L. Crow. *Mining Engineering*, v. 9, July 1957, p. 750-752.
Determining the optimum size assortment of grinding balls for a makeup charge is a practical means of improving mill operation.

Détermination de la puissance absorbée dans les broyeurs à boulets et de la puissance perdue par le glissement de la charge.
Determining the Absorbed Power in Grinding Mills and That Lost by the Sliding of the Charge.
V. Freymann. *Revue des Matériaux de Construction*, C, Feb. 1957, p. 55-62.

Grinding Temperatures.
J. E. Mayer, Jr. and M. C. Shaw. *Lubrication Engineering*, v. 13, Jan. 1957, p. 21-27.
Apparatus for measuring the temperature of a freshly ground surface by means of a photoconducting PbS cell and an ocsilloscope is applied to a study of the influence of different grinding fluids.

The Effect of the Grinding Procedure on Development of Channels on Porous Chromium. (in Russian)
A. A. Mikhailov. *Vestnik Mashinostroeniia*, v. 36, no. 9, Sept. 1956, p. 52-56.
Data on the influence of various factors in grinding metal parts prior to Cr plating, on the extent of the channel network on the porous Cr coating. Number of channels increases with the force applied in the grinding.

New Views on Grinding and Polishing, Especially Metallographic Polishing. (in Czech.)
Zdeněk Ministr. *Hutník*, v. 6, no. 9, Sept. 1956, p. 257-262.
Theoretical considerations. Excellent results obtained by using diamonds dispersed in a paste.

Proper Truing and Dressing Means Better Toolroom Grinding.
John A. Mueller. *Metalworking Production*, v. 100, Nov. 2, 1956, p. 1775-1780.
Ways to avoid grinding troubles, such as chatter, burning, cracking, and rough surfaces, are recommended on the basis of a series of controlled tests.

How Much Do Grinding Fluids Affect Wheel Performance? I.
J. A. Mueller, *Iron Age*, v. 179, Feb. 28, 1957, p. 79-81.
Tests with gases, water-soluble oils, and straight oils. Amount of metal removed, wheel wear, power consumed, workpiece finish, and cutting rate were measured.

Cost-Cutting With Grinding Wheels. I. Snagging Wheel Speed Control.
John. A. Mueller. *Modern Castings*, v. 31, Feb. 1957, p. 62-64.
Control of surface speed is first step in planning snagging operations that will remove metal, faster, at lower cost.

Cost Cutting With Grinding Wheels. II. Work Pressure and Wheel Selection.
John A. Mueller. *Modern Castings*, v. 31, Mar. 1957, p. 34-35.
Work pressure has drastic effect on wheel life and cutting rates, paricularly with softer wheels.

Cutting and Grinding Ceramics.
R. F. Rea and J. W. Ripple. *American Ceramic Society Bulletin*, v. 36, May 1957, p. 163-167.
With modern grinding facilities and techniques, finish tolerances of $\pm$0.0001 or better may be obtained. Grinding also provides improved surface finishes, the quality of which depends on the abrasive used, the body being ground, and grinding practices.

Inorganic Grinding Fluids for Titanium Alloys.
M. C. Shaw and C. T. Yang. *American Society of Mechanical Engineers, Paper* No. 55-SA-39, 1955, 14 pp. (TJI Am35p Contin.)
Dilute inorganic aqueous solutions are effective grinding fluids for Ti alloys due to the formation of adsorbed layers on both the grinding wheel and freshly ground Ti surfaces. Barium was most effective for Al_2O_3 surfaces, and the phosphate radical for Ti surfaces.

Ultrasonic Impact Grinding Produces Precise Shaped Holes, Slots on Servo-Valves With Ease.
A. E. Shumate *Western Metals*, v. 15, Feb. 1957, p. 41-43.
Cutting or shaping hard or brittle materials. Tool vibrates 25,000 c.p.s.

7.4. *Finishing*

Finishing Methods for Aluminium.
Product Finishing, v. 10, Mar. 1957, p. 82-99.
Cleaning methods; mechanical finishes; chemical, anodizing, and electropolishing treatments; coloring anodic coatings.

Lapping for Precision Ceramics.
Steve Boetcher. *Ceramic Age*, v. 68, Nov. 1956, p. 26-29.
Lapping is an economical method of removing substantial amounts of material with tolerances as low as $\pm$ 0.0001.

Metal Polishing With Set-Up Wheels.
R. S. Burt. *Metal Finishing*, v. 55, Feb. 1957, p. 52-55.
Types of adhesives and abrasives; preparation of wheel for set up; paste heading, drying, and breaking up of wheel surface.

Some Aspects in the Production and Measurement of Surface Finish.
M. A. Chapple. *Australasian Engineer*, v. 49, May 1957, p. 57 + 3 pages.
Precision grinding; diamond lapping; types of machines used to check surface finish.

Buffs for All Purposes.
Edwin F. Doyle. *Metal Finishing*, v. 54, Dec. 1956, p. 56-61, 70.
Brief description of various types of buffs that are widely used. Outstanding qualities and the types of work each is best suited for.

Traitement des surfaces en vue de la galvanisation: le dégraissage.
Surface Treatment Prior to Galvanization: Scouring.
A. Herz. *Métallurgie et la Construction Mécanique*, v. 89, Jan. 1957, p. 49 + 1 page.
Generalization of scouring by use of an alkaline solution, surface tension, wetting agents, and influence of pH.

Maize Cellulose.
William V. Karr. *Industrial Finishing (London)*, v. 9, June 1957, p. 642-644.
Use of maize cellulose in the plating and finishing industry for drying, polishing, and burnishing and as a filler, conditioner, and absorbent.

Das Glattwalzen, ein spanloses Verfahren der Feinbearbeitung.
Roll Finishing, a Noncutting Finishing Process.
Helmut König. *Zeitschrift für Metallkunde*, v. 48, June 1957, p. 366-370.
The practical application of a smooth rolling technique with reference to deformation processes in the surface. Changes in surface hardness, internal stresses, and surface roughness limit applicability.

Quality of Ground Surfaces. (in Czech.)
J. Říčka. *Strojírenství*, v. 6, Dec. 1956, p. 823-830.
The finish of machine parts as a factor in determining their proper function. Surfaces

obtained by grinding. Factors determining the roughness of ground surfaces. Basic technological conditions of grinding and their effect upon the finish.

Finishing Nickel and High Nickel Alloys.
Lester F. Spencer. *Metal Finishing*, v. 55, Mar. 1957, p. 50 + 6 pages.
Recommendations for roughing down welds, polishing, buffing, brushing, and bobbing; materials used for finishing; specific examples.

Industrial Honing. I.
D. Warburton-Brown. *Machinery Lloyd (Overseas Ed.)*, v. 28, Nov. 10, 1956, p. 70-71, 73-75.
Factors affecting honing performance; abrasives and their classification; cutting action of abrasive grits.

Industrial Honing. III.
D. Warburton-Brown. *Machinery Lloyd (Overseas Ed.)*, v. 29, Jan. 19, 1957, p. 69-75.
Honing fluids; stock removal; honing tools.

Industrial Honing. V.
D. Warburton-Brown. *Machinery Lloyd (Overseas Ed.)*, v. 29, June 22, 1957, p. 70-77.
Equipment; the nature of machined surfaces; correction of errors by honing; bell mouthing; effect of surface interruptions; blind bores; external honing; field of application.

8. Machining and Metal Working

8.1. *Cutting Tools and Cutting*

How Are Your Carbide Tools Performing? II.
Machinery, v. 63, Mar. 1957, p. 195-202.
Effect of tool shape, speed, feed, depth of cut, and coolant on the life of carbide tools.

Guide to Carbide Tool Geometry.
Steel, v. 141, July 8, 1957, p. 110-111.
Recommended cutting angles for seven types of metal are tabulated.

Constant Surface Cutting Speed Saves Time and Tools.
A. S. Albrecht. *Iron Age*, v. 180, July 18, 1957, p. 124-126.
Data shows how cutting speed affects tool life, resulting finish, and accuracy.

New Techniques in Metal-Cutting Research.
W. R. Backer and E. J. Krabacher. *ASME, Transactions*, v. 78, Oct. 1956, p. 1497-1505.
Newly developed methods for studying this process. Tool-wear and grinding-wheel-wear measurement methods. Equipment for studies of the mechanics of machining processes.

Contribution to a Solution of the Problem of Short Duration Tests for Determining the Life of Turning Tools.
E. Bickel. *Microtecnic (English Ed.)*, v. 10, no. 5, 1956, p. 209-214.
Derivation of curves for predicting tool life using data acquired in tests requiring only 10 to 25 min.

Force Relationships in the Machining of Low-Carbon Steels of Different Sulphur Contents.
F. W. Boulger, H. E. Hartner, W. T. Lankford, and T. M. Garvey. *ASME, Transactions*, v. 79, July 1957, p. 1155-1164.
Tests on steels with 0.025 to 0.250% S content in constant pressure and conventional lathes showed that S addition reduced the forces acting on the tool for equivalent feeds. This effect results from decreased friction between chip and tool and from an accompanying reduction in strain during chip formation.

Metal-Cutting Evaluation.
F. J. Daasch. *Steel Processing and Conversion*, v. 43, Mar. 1957, p. 136-141.
Current status of various techniques. All are based on one or more of four factors: tool life, tool forces, surface quality of finished work, and power consumed.

Concentration Effects of Cutting Oil Additives in Performance Evaluation.
A. Dorinson. *Lubrication Engineering*, v. 12, Nov.-Dec. 1956, p. 387-391.
Tests including turning, planing, and tapping demonstrated the concentration-dependent activity of additives in cutting oils.

Extending the Durability of High-Speed Drills and Cutting Tools. (in Czech.)
F. Drábek. *Strojírenská Výroba*, v. 5, May 1957, p. 196-200. A survey of the effects of various methods of increasing tool durability.

Effect of Pressure Between Tool Tip and Workpiece on the Rate of Ultrasonic Machining in Ketos Tool Steel.
Dieter Goetze. *Acoustical Society of America, Journal*, v. 29, Apr. 1957, p. 426-431.

Cutting-Fluid Evaluation.
H. W. Husa. *ASME, Transactions*, v. 79, July 1957, p. 1172-1176.
Transfer of radioactive material from a cutting tool to the chips produced in facing the end of a steel tube is used as a means

of measuring tool-wear rate. In addition to this, evaluation of a cutting oil may require consideration of the roughness of the cut surface or the cutting temperature.

Le mécanisme de la coupe des métaux.
The Mechanics of Metal Cutting.
Roger Jouty. *Publications Scientifiques et Techniques du Ministère de l'Air*, no. 326, 1957, 98 pp. (TL502 F84.1p Vis.)
Mechanism of chip formation. Part played by the sliding and rubbing between the chip and the face of attack. Tests with a two-component dynamometric tool holder. Increase of temperature. Deformation and friction energies. Tool vibrations.

The Phenomenon of Cutting.
O. Kienzle. *Microtecnic* (*English Ed.*), v. 10, no. 6, 1956, p. 253-256.
Phenomena associated with shearing sheet metal by means of a punch and die. Factors influencing quality of cut surfaces; burr formation; wear of cutting tools.

Research on the Cutting Performance of Fine-Grain Abrasive Stone.
Tokio Sasaki and Kenjiro Okamura. *Kyoto University, Memoirs of the Faculty of Engineering*, v. 18, Oct. 1956, p. 354-366.
Of the constitutional factors, porosity has the most influence on cutting performance.

An Analysis of the Orthogonal Boring Operation.
Bernard W. Shaffer. *ASME, Transactions*, v. 78, Oct. 1956, p. 1517-1525.
Under prescribed conditions, a shear-angle relationship, an expression for machining force, and an expression for the chip-thickness ratio were derived.

The Friction Process in Metal Cutting.
Iain Finnie and M. C. Shaw. *ASME, Transactions*, v. 78, Nov. 1956, p. 1649-1657.

On the Wear of Cutting Tools.
M. C. Shaw and S. O. Dirke. *Microtecnic* (*English Ed.*) v. 10, no. 4, 1956, p. 187-193.
Nature of wear and metal transfer is developed and applied to explain the wear performance of cutting tools. Underlying reasons behind trends observed in tool-life testing.

The Influence of Lead on Metal-Cutting Forces and Temperatures.
M. C. Shaw, P. A. Smith, E. G. Loewen, and N. H. Cook. *ASME, Transactions*, v. 79, July 1957, p. 1143-1154.
Effects of additions of Pb and S to steel upon tool-face friction, cutting energy per unit volume, and tool-face temperature.

Leaded Steel and the Real Area of Contact in Metal Cutting.
M. C. Shaw, P. A. Smith, N. H. Cook, and E. G. Loewen. *ASME, Transactions*, v. 79, July 1957, p. 1165-1171.
The real area of contact between chip and tool is between 1 and 2% of the apparent area of contact. The cutting characteristics of steels containing Pb are compared with those for steel without Pb as well as those for pure Pb.

Stream Treat Tools for Longer Shop Life.
F. L. Spangler and M. E. Lackey. *Iron Age*, v. 179, June 17, 1957, p. 106-108.
Steam treating increases tool life by putting a controlled oxide film on tool surfaces.

A Method of Assessing the Progress and Behavior of Wear Patterns on Tungsten Carbide Tools and Some Possibilities for Interpretation.
E. Y. C. Sun and W. B. Heginbotham. *Microtecnic* (*English Ed.*), v. 11, no. 2, 1957, p. 71-75.
Apparatus and techniques.

Study on Wear Process of Carbide Tools.
Hidehiko Takeyama, Terumi Murai, and Eiji Usui. *Journal of Mechanical Laboratory* (*Japan*), v. 2, no. 2, 1956, p. 14-24.
Characteristics of tool life when the high class cast iron FC27 and the Ni-Cr-Mo steel SNCM 3 are machined with *G* and *S* series carbides respectively.

Zur spanabhebenden Bearbeitung von Kupfer und Kupferlegierungen mit Hartmetallwerkzeugen.
Metal Cutting of Copper and Copper Alloys With Hard Metal Tools.
J. Witthoff. *Technische Mitteilungen Krupp*, v. 14, no. 5, Nov. 1956, p. 123-131.
Grinding, lapping, and polishing of different types of Cu and Cu alloys; various phases of machining.

8.2. *Special Methods*

Special Theory of Ultrasonic Machining.
George E. Miller. *Journal of Applied Physics*, v. 28, Feb. 1957, p. 149-156.
A model is proposed for the mechanism of material removal in ultrasonic machining. From this model and fundamental physical principles, a machining rate equation is derived for the special case where solid, circular tools are used in conjunction with a puddled slurry.

Ultrasonic Machining. II. Operating Conditions and Performance of Ultrasonic Drills.
E. A. Neppiras and R. D. Foskett. *Philips Technical Review*, v. 18, no. 12, 1956/57, p. 368-379.
Cutting speeds, accuracy, and surface finish are considered.

The Technology of Electro-Spark Machining. (in Czech.)
Jindřich Staněk. *Elektrotechnik*, v. 12, Jan. 1957, p. 2-7.
Method for machining hard materials based on the erosion of the metal by spark discharges between the tool electrode and the part being machined.

8.3. *Processing*

Untersuchungen an einem Vierwalzen-Kaltband-Umkehrgerüst für Weissblech.
Investigations on a Four-High Reversing Mill Stand Rolling Cold Strip for Tinplate.
I. Messungen zur Bestimmung des Kraft- und Arbeitsbedarfes und des Ausnutzungsgrades.
Measurements to Determine the Power and Work Required and the Degree of Utilization.
Karl Heinz Spiller.
II. Einfluss von Walzkraft, Walzgeschwindigkeit, Bandzug und Schmierstoffmenge auf die Masshaltigkeit des kaltgewalzten Bandes.
Effect of the Rolling Force, Rolling Speed, Strip Tension and Amount of Lubricants Used on the Trueness to Dimensions of the Cold-Rolled Strip.
Paul Funke. *Stahl und Eisen*, v. 77, June 27, 1957, p. 867-881.

Partial Sideways Extrusion From a Smooth Container.
W. Johnson. *Journal of the Mechanics and Physics of Solids*, v. 5, no. 3, 1957, p. 193-201.
Effects of unusual locations of the die with respect to the direction of motion of the punch were examined.

Titanium Extrusions.
A. M. Sabroff and P. D. Frost. *Modern Metals*, v. 13, June 1957, p. 50 + 4 pages.
A summary of available information on extrusion of Ti and its alloys; probable demand and requirements and progress in meeting it; firms that have extruded Ti; extrusion practices; tooling; heat treating; mechanical properties of extrusions.

Authors' Abstracts

WEAR TESTING

A Constant Torque Abrader with a Permanent Abrasive Surface

Ira Williams, J. M. Huber Corp., Borger, Tex.

Abstract of a lecture given before the Rubber Division ACS, Montreal Conference, May 1957. *Rubber World, 136* (April 1957) 75.

The Graselli Du Pont abrader has been modified to provide variable speed and to operate at any predetermined constant rate of work. The round test disks are rotated flat against the abrasive surface at the same r.p.m. as the abrasive disk. This practice assures a uniform rate of wear on the entire surface and provides an abrasive action in every direction. The test pieces and the abrasive disk are enclosed in a cabinet which may be heated.

The abrasive surface is a metal disk with 30 mesh carborundum grit sparsely bonded with a modified epoxy resin. Such disks are easily duplicated within $\pm$ 2% and have maintained unchanged cutting power on tread stocks for six million revolutions. Such a disk becomes a standard for the measurement of abrasion. A constant talc feed effectively protects the abrasive from becoming smeared by any type of compound, and the cutting rate remains unchanged regardless of the type of compound previously tested.

While the machine is capable of reproducing results within 2% or 3%, it will not predict the service life of a compound. It appears to predict reliably the relative performance of compounds using the same basic matrix. This machine is useful in studying the effect of such factors as amounts and types of pigmentation or the effect of chemicals or temperature of operation or rate of slip within one basic matrix. No abrasion machine will compare compounds such as SBR, oil-extended SBR, or butyl rubber based on a widely different matrix, but may compare compounds based on such similar elastomers as natural and SBR rubbers, provided the other substances in the matrix are the same.

Estimating Wear of Combustion Engines by Means of Oil Tests (in Dutch)

F. P. Malschaert, University of Gent (Belgium). *De Ingenieur, 69*, no. 28 (1957), M 9-17 (4 fig., 15 tables, 31 ref.).

The first part of the paper gives a brief survey of several principles and methods according to which the chemical testing of the lubrication oil used in a combustion engine may result in determining its content of different metals, finely distributed or dissolved as organo-metal salts. The precipitate or the sludge detained in the oil filter is not to be neglected in any case, because modern filters detain more impurities than those present in the motorhouse.

The second part describes the rather extensive application of the spectrographical testing method used in the laboratory in order to measure the relative wear of automobile motors using gasoline with or without the addition of a dope.

The results prove that wear is reduced by the dope and that the testing method is sensitive enough to detect even small differences in the wear of motors.

Radioactive Cutting Tool and Piston Ring Wear Tests

A. J. Snow and H. C. Skonecke, (Sinclair Res. Lab. Inc., Harvey, Illinois, U.S.A.). — *Atompraxis* (Karlsruhe, Germany) *3*, no. 8/9 (1957) 299-306; (12 fig., no ref.)

Radioisotopes are currently being used at Sinclair Research in accelerated wear tests on cutting fluids and motor oils.

Radioactive cutting tool tips are used to measure the effect of various cutting fluid formulations on cutting tool face and flank wear. The cutting tool tests are run on a standard milling machine with the radioactive tool completely enclosed in an adequately shielded cutting chamber. Cutting fluid test data are run on a comparative basis with the experimental fluid wear rate compared against that of a known reference fluid wear rate. Experimental arrangements, shielding, and sample data are given.

Piston ring wear as a function of oil composition and engine operating conditions is measured by use of a radioactive top compression ring on a single cylinder COT test engine. Engine oil is pumped from the crankcase through a cooler, counter, reheater, and back into the engine. Major initial problems in this test setup included stagnant oil in the counting chamber, variable oil flow rates through the external oil circulation system components, and dispersant characteristics of certain oils. Experimental arrangements and sample data are given.

Both of these test techniques employ large sodium iodide crystals as gamma ray detectors. These scintillation detectors allow the use of lower activity radioisotopes than conventional geiger tube detectors and more rapid counting techniques. Safety procedures and routine daily operation of this test equipment with non-technical personnel are described. No difficulties have been encountered in keeping the radiation exposure of all personnel well below the authorized AEC level.

GRINDING

Experiments on Electrolytic Grinding (in Dutch)

P. Landberg, J. L. Remmerswaal (Technical University and T.N.O., Delft) — *Metaalbewerking*, *22*, no. 22 and 23 (1957); (10 fig., 9 ref.). Commun. no. 50 of the *Metal Research Institute T.N.O.*

The process of electrolytical grinding of tungsten carbide with a nickel-bonded diamond wheel gives a considerable saving of diamond in comparison with ordinary grinding. The rate of metal removal is greater than by the normal grinding process. The surface quality of the ground work is not as good as with ordinary grinding.

The rate of attack was greater with a more diluted electrolyte and with a stronger current. For a better surface quality a weaker current must be used.

Recent Events

U.S.A.

DISCUSSION ON FRICTION AT GENERAL MOTORS

A discussion on friction was held on June 10th and 11th at the Technical Center of General Motors Corporation, Detroit. The eight lectures on friction and wear were attended by over one hundred people; they will eventually be published in book form.

The interest of engineers in this field is best summed up by Dr. HAFSTAD's introductory remarks: "In furthering knowledge of friction we (General Motors) cannot lose because if we increase friction we will have good brakes, if we eliminate friction we will have good engines".

Dr. F. P. BOWDEN (Cambridge) spoke on "Recent studies of the friction of solids". Dr. A. T. GWATHMEY and Dr. L. DYER (University of Virginia) presented a paper on "Cohesion between two oriented single crystals of copper", Dr. ROBERT DAVIES (G.M.) — the program chairman — described "A tentative model for the mechanical wear process". R. DRUTOWSKI (G.M.) discussed "Energy losses of balls rolling on plates" and C. GOODZEIT (G.M.) spoke on "The seizure of metal pairs during boundary lubrication". Additional contributions came from M.I.T., G.E. Research Lab., and U.S. Naval Research Laboratory.

Source: G.M. Research Staff. (Ed.)

Germany

GEARS

(Zahnräder und Zahnradgetriebe 1957)

A meeting on gears was held on September 5th-6th, 1957, at Technical University, Dresden (Germany, D.D.R.).

The lectures (see below) will be published as "KBS-Nachrichten" and can be purchased from: Kammer der Technik, Fachverband Maschinenbau, Ebertstrasse 28, Berlin W 8. Price D.M. 4.00.

Dr.-Ing. RETTIG, *München*	Beitrag zur Berechnung und Gestaltung gehärteter Stirnräder
Dr.-Ing. FRONIUS, *Dresden*	Beitrag zur Berechnung und Gestaltung ungehärteter Stirnräder
Prof. Dr.-Ing. WEINHOLD, *Magdeburg*	Zahnradfehler, ihre Bestimmung und ihre Auswirkung.
Dr.-Ing. habil. BUDNICK, *Ludwigsburg*	Verzahnungstoleranzen in Theorie und Praxis.
Dr.-Ing. HIRSIEG, *Düsseldorf*	Getriebe mit Zylinderschnecken.
Prof. SAIKIN, *Moskau*	Globoidgetriebe.
Dr.-Ing. SCHRÖDER, *Karl-Marx-Stadt*	Herstellungsverfahren von Kegelrädern.

Switzerland

SCHWEIZERISCHE VERBAND FÜR DIE MATERIALPRÜFUNGEN DER TECHNIK

(Swiss Association for the Testing of Materials)

The 235th discussion held at Zurich on September 5th and 6th, 1957, was devoted to the wear of roads, some general wear problems, and wear problems in turbines.

The discussions were held under the chairmanship of the President of the Association, Professor A. VON ZEERLEDER.

1. General introduction

H. WAHL *(Stuttgart)*

Definitions, Systematics and Standardization of Wear Testing was discussed along the lines of thought given on p. 211 of this issue. Many details have been published previously (in German) in *Metalen*, 9 (no. 4, 5 and 6) (1954).

New results were reported on the wear of drills for rock-drilling. The influence of water and surface-active liquids on the growth of microcracks in the bit has been studied. It follows from microscopic observation that wear is due to fissuring and breaking out of material rather than to gradual abrasion of the drill.

2. Gleit-, Spül- und Strahlverschleissprüfung

K. WELLINGER *(Stuttgart)*

See p. 225 of this issue. Some additional data will be published in *Schweiz. Arch. angew. Wiss. u. Tech.*, (1957/58).

3. Abrasion caused by sand-carrying water in hydraulic plants (in German)

W. STAUFFER *(Escher-Wyss, Zurich)*

The importance of wear due to sand erosion in water turbines and pumps, is pointed out. A new method for the evaluation of wear-resistant materials has been developed in the laboratories of Escher-Wyss: it is a rigidly standardized "abrasion pan" (see the papers by WAHL and by WELLINGER in this issue).

Extreme differences up to 1:500 in the abrasion resistance of 150 materials were found, but within one group, *e.g.* steel, the figures of merit differed only by a factor of 6. The influence of the rate of rotation and of the "abrasivity" of the abrasive were studied, and limited correlations with the hardness of the abrasive were established. *Schweiz. Arch. angew. Wiss. u. Tech.*, (1958).

4. Damage due to droplets and to cavitation in hydraulic and steam turbines (in German)

A. KELLER *(Escher-Wyss, Zurich)*

Phenomenological and technological discussion of these wear processes. Laboratory testing of cavitation with a number of standardized apparatuses was coordinated with the work of the previous speaker.

Titanium alloys were shown to resist cavitation exceptionally well, but are not yet of use as materials in turbines. *Schweiz. Arch. angew. Wiss. u. Tech.*, *23* (1957) 346.

5. Contributions to the study of erosion phenomena due to friction in the field of hydraulic turbines (in French)

TH. BOVET *(Ecole Polytechnique de l'Université, Lausanne)*

After discussing the type of wear due to sand-carrying water and a theoretical approach to the problem in Pelton, Francis and Kaplan turbines, interesting data on the variability of solid matter in alpine torrents and rivers were presented. Efficient and practical measures to combat this cause of wear were reported. *Schweiz. Arch. angew. Wiss. u. Tech.*, (1957) in the press.

6. The wear of roads

A full day was devoted to survey lectures from experts in neighbouring countries.

(a) J. OBERBACH *(STRABAG, Köln)* (in German)
gave a systematic classification of the problems involved. Abrasion of the road surface is of minor importance: the wear of roads is a deterioration process. Economic factors and other considerations, such as safety and ease of repair, determine the choice of an optimum road compound. *Schweiz. Arch. angew. Wiss. u Tech.*, *23* (1957) 361.

(b) J. MIEGL *(TEERAG, Vienna)* (in German)
discussed the present situation in Austria, emphasizing again the economic factors as well as the need for exchanging experience. *Schweiz. Arch. angew. Wiss. u. Tech.*, (1957) in the press.

(c) R. ARIANO *(Scuola Politecnica, Milano)* (in French)
gave an exposition of slip problems, and suggested new methods to overcome the arbitrary definition of frictional coefficients of road surfaces.

(d) M. DURIEZ *(Laboratoire de recherches et d'essais, Paris)* (in French)
communicated some of his experience gained as general inspector of the French roads. A distinction was made between various types of deterioration of road surfaces. The most interesting one was the parallel drawn between the fatigue of metals and the road wear due to large amplitudes of deformation under the influence of heavily loaded vehicles. *Schweiz. Arch. angew. Wiss. u. Tech.*, *23* (1957) 366.

England

CONFERENCE ON

Lubrication and Wear

The conference announced on page 74 (Issue 1) of this journal was attended by more than 800 delegates from more than 20 countries.

104 Papers were selected for presentation and were available as preprints. 9 Reviewers analysed this material in 5 general and 3 special sessions. The bulk of the contributions came from U.K., U.S.A. and U.S.S.R. The Proceedings of the Conference will contain in addition the discussions held not only at the London Conference but also at the New York meeting of the A.S.M.E. (in December 1957). No doubt this monumental volume will influence the course of research on wear in many quarters.

With the kind permission of the Council of the I.M.E., and commencing with this issue, WEAR will print some of the review articles in a condensed form and others as abstracts. Preprinting of these surveys and the appended bibliographies will enable readers to select their field of interest from this somewhat terrifying multitude of papers.

Ed.

The Netherlands

ASSOCIATION FOR THE STUDY OF MATERIALS

and

ROYAL (NETHERLANDS) INSTITUTION OF ENGINEERS

1. A lecture was given to the Lubrication Sections of both groups at The Hague on October 17th, 1957 by Dr. W. ARNDT (Germany) on:

Grade testing with the four-ball machine; a new method for the evaluation of wear protection given by motor and gear oils.

To be published in *Erdöl und Kohle*.

2. A full day discussion was held at Utrecht on November 22nd, 1957, on the I.M.E. Conference (London) on

LUBRICATION AND WEAR

Reviewers were: Prof. H. BLOK (Delft),
J. J. BROEDER, chem. Drs. (Royal-Dutch/Shell, Amsterdam), and
Dr. Ing. G. SALOMON (T.N.O., Delft).

Notes on Contributors

C. M. ALLEN, B.E.: known for his work on bearing problems and in the related fields of friction, lubrication, and wear phenomena; Battelle Institute consultant; in this capacity devotes his attention to the technical planning and guidance of research programs in these fields. Received his B.E. degree in mechanical engineering and metallurgy from the University of Toledo in 1941; joined the Battelle staff in 1943 as a research engineer; is a member of the American Society of Lubrication Engineers (including membership on the subcommittee for sliding contact bearings) and the Society for Automotive Engineers, and author of several technical papers.

[See p. 232]

ROBERT B. CAMPBELL, B.Sc., Ph.D.: born in Liverpool; graduated B.Sc. with honours in chemistry from the University of Glasgow in 1949; carried out research in X-ray crystallography under Prof. J. M. Robertson, gaining degree of Ph.D. in 1952. In that year joined the Physical Metallurgy Section of the Culcheth Laboratories of the Department of Atomic Energy as a scientific officer; in 1953 transferred to the Lubrication Division of the Mechanical Engineering Research Laboratory, Department of Scientific and Industrial Research, where he is now a senior scientific officer. Present interests are the chemistry of lubrication, in particular the application of radioactive and X-ray diffraction techniques to problems of boundary lubrication and wear.

[See p. 173]

C. B. Davies, M. A. (Cantab.), Ph.D. (Cantab.): born at Swansea; studied at Cambridge University, where he obtained his M.A. and Ph.D., specializing in physical chemistry. For 15 years carried out research with the Royal Dutch-Shell Group, specializing in lubrication studies; at present, manager of the Thornton Research Centre, "Shell" Research Ltd., Chester. [See p. 244]

J. de Vries, Ir.: Mechanical engineer, Delft, 1924. Engineer and chief engineer with the Government Railways in Indonesia, 1926-1952, (temporarily interrupted by the war and by activities at the Ministry of Economic Affairs of East-Indonesia). Since 1953 engineer at the Royal Netherlands Blast-furnaces and Steel-works, IJmuiden. [See p. 239]

Gerald S. Harriden: born in Reigate, Surrey; apprenticed in the machine shop and diesel and petrol engine departments of Hall & Co. Ltd. and then completed his training in the drawing office; gained the Senior National Certificate in Mechanical Engineering at Redhill and Coatbridge Technical Colleges and endorsements at the Royal College of Science and Technology, Glasgow. In 1950 joined the Lubrication and Wear Division of the Mechanical Engineering Research Laboratory, Department of Scientific and Industrial Research, as an assistant experimental officer, and since then has been engaged in experimental work and design of experimental equipment for research into problems connected with friction and wear; is now an experimental officer in this organization. [See p. 173]

F. F. Ling: born in Tsingtao, China; received B.S. in civil engineering from St. Johns University, China; B.S. in mechanical engineering from Bucknell University, U. S. A.; M.S. and D.Sc. in mechanical engineering from Carnegie Institute of Technology. Currently, assistant professor of mechanics at the Rensselaer Polytechnic Institute, Troy, N.Y.; interested in mechanics, particularly in the mechanics of friction and wear. [See p. 167]

P. P. Love, B.Sc.; educated at Alan Glen's School, Glasgow. In 1935 graduated with honours in mechanical engineering at Glasgow University; during the tenure of a Whitworth Scholarship carried out investigations into systems of power transmission; served in the Royal Air Force during the war and was released in 1943 to become chief engineer of a factory of The Glacier Metal Company, Ltd. After a short period with Hymatic Engineering Co. Ltd., re-joined Glacier Metal Company, subsequently became general manager of the Research and Development Organization, and in 1955 was elected a director of the Company. [See p. 196]

Herman Ortner, Dipl.-Ing.: born at Magdeburg (Germany); studied at the Institute of Mining Technology, Leoben; at present, engineer with the South African Iron and Steel Corporation, in Pretoria. [See p. 183]

Edward Saibel: born in Boston, Mass.; received degree S.B. from Massachusetts Institute of Technology 1924; studied at Cornell University 1924-1926; received degree Ph.D. from Massachusetts Institute of Technology 1927. Taught at University of Minnesota 1927-1930; since 1930 at Carnegie Institute of Technology; subsequently professor of mechanics in the Department of Mathematics. From September 1, 1957, professor of mechanics at Rensselaer Polytechnic Institute, Troy, New York. [See p. 167]

Herbert Uetz, Dr.-Ing.: born at Schwäbisch Gmünd, Württ. (Germany); studied engineering at the Technische Hochschule, Stuttgart; 1949 and 1950 research officer at the Department for mechanics, study of materials and material testing; now expert in wear problems at the Government Laboratory for the testing of materials. [See p. 225]

H. Wahl, Dr. Ing. habil.: born at Kirchheim/Teck (Germany); studied mechanical engineering, followed by development work on carbon dust motors; encountered here for the first time numerous practical wear problems (Thesis, Berlin 1934). Founded and directed a wear research laboratory. Since 1946 independent consultant laboratory; has carried out work on metal-minerals wear and on the production of wear-resistant materials; chairman of the Working Committee D 4 b for wear problems, a task group of the German Standards Organization. [See p. 211]

Richard G. Walzel: born at Neunkirchen, Austria; studied at the Institute of Mining Technology, Leoben; Dipl.-Ing. and Doctor in mining science. Since 1933 ordinary professor of iron metallurgy and head of the department at the Institute of Mining Technology, Leoben. Has often dealt with wear problems; since 1928 has had a significant influence on the development of highly wear-resistant rails made from "one-compound" alloys; further, has also studied other problems in the fields of metallurgy and materials technology of iron and steel. [See p. 183]

K. Wellinger, Prof. Dr.-Ing. habil.: born in Stuttgart; studied engineering at the Technische Hochschule, Stuttgart; head of the department and director of the Government Laboratory for the testing of materials, Technische Hochschule, Stuttgart. [See p. 225]

THE MECHANISM OF BOUNDARY LUBRICATION AND THE PROPERTIES OF THE LUBRICATING FILM

SHORT- AND LONG-RANGE ACTION IN THE THEORY OF BOUNDARY LUBRICATION

B. V. DERYAGUIN

Corresponding Member of the Academy of Sciences of U.S.S.R.

in collaboration with

V. V. KARASSEV, N. N. ZAKHAVAEVA AND V. P. LAZAREV

Laboratory of Surface Phenomena, Institute of Physical Chemistry, Academy of Sciences of U.S.S.R., Moscow (U.S.S.R.)

SUMMARY

Two versions of the blow-off method are described, by means of which the dependence of the viscosity of oils and other non-volatile fluids on the distance from the solid wall can be measured, and the viscosity localized with an accuracy of 10 Å.

In the case of non-polar specially purified vaseline oil the viscosity remains strictly constant to a distance of the order of 10^{-7} cm from the wall. The addition of polar additives causes changes in the viscosity near the wall. In a number of cases the viscosity changes discontinuously at some distances of the order of 10^{-6} to 10^{-5} cm from the wall. In the case of polar liquids the viscosity may rise or fall on approaching the wall, depending on the molecular structure.

The results obtained prove that the solid wall is capable of altering the orientation of the molecules in adjacent layers of the liquid up to 10^{-5} cm thick, and even up to 10^{-3} cm thick in the case of polymeric liquids. This effect plays a substantial part in the mechanism of boundary lubrication, since oiliness always disappears if it is absent.

In conclusion, an examination is made of the mechanical properties of the boundary lubrication layer which explain both the existence of static friction and the observation of the two-term friction law derived by DERYAGUIN from the molecular theory of friction.

The general conclusion is the impossibility of accounting for the phenomenon of boundary lubrication without taking into consideration the specific properties of the polymolecular boundary layers of liquids.

ZUSAMMENFASSUNG

Zwei verschiedene Varianten der sogenannten Abblas-methode werden beschrieben. Diese erlauben es die Abhängigkeit der Zähigkeit von Ölen und anderen nicht-flüchtigen Flüssigkeiten als Funktion des Abstandes von der festen Wand zu messen und die Zähigkeit mit einer Genauigkeit bis auf 10 Å zu lokalisieren.

Für ein nichtpolares speziell gereinigtes Vaselinöl bleibt die Zähigkeit streng stabil bis zu einem Abstand von der Wand von der Grössenordnung 10^{-7} cm. Zufügung polarer Substanzen zu dem Öl hat eine Veränderung der Zähigkeit in der Nähe der Wand zur Folge. In einer Reihe von Fällen verändert sich die Zähigkeit sprungweise und zwar bei einem Abstand von der Wand von der Grössenordnung 10^{-6}—10^{-5} cm. Für polare Flüssigkeiten kann die Zähigkeit abhängig von der Struktur von Molekülen, entweder zunehmen oder abnehmen.

Versuchsergebnisse zeigen, dass eine feste Wand die Orientierung der Moleküle von Flüssigkeitsschichten bis auf einen Abstand von 10^{-5} cm und für polymere Flüssigkeiten sogar bis auf 10^{-3} cm beeinflussen kann. Diese Erscheinung spielt eine bedeutende Rolle in dem Mechanismus der Grenzschmierung denn, wenn sie nicht auftritt verschwindet auch regelmässig die Schlüpfrigkeit.

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Zum Schluss wird die Frage der mechanischen Eigenschaften der Grenzschichten von Flüssigkeiten besprochen, mit deren Hilfe sowohl die Existenz der statischen Reibung als auch die Gültigkeit des binomialen Reibungsgesetzes, das DERYAGUIN aus der molekulären Theorie der Reibung ableitete, erklärt wurden.

Als allgemeines Ergebnis der Untersuchungen wird festgestellt: Die Erscheinung der Grenzschmierung sind nicht zu erklären ohne die spezifische Eigenschaften der polymolekularen Grenzschichten von Flüssigkeiten in Betracht zu ziehen.

INTRODUCTION

The far greater complexity of the phenomena of boundary friction as compared with fluid friction is due to the fact that the former is in the main affected by the molecular interaction between the solid surfaces and the boundary lubricating film in contact with them, an interaction which modifies the properties of the film. This is the dominant factor in the case of friction when the lubricating film is thin, whereas viscosity which alone determines the phenomena of fluid friction is of lesser importance at the small velocities at which boundary friction, and especially, static friction, usually takes place. Since experimental investigation of the properties of the boundary lubricating film is very difficult, the mechanism of boundary lubrication has been insufficiently studied up to now.

At present there are two opposing views on the mechanism of boundary lubrication. The first, worked out in detail by BOWDEN[1], proceeds from the assumption that boundary friction is noticeably affected only by the properties of the friction surfaces themselves or of the monomolecular layers adsorbed on them. The layers of the lubricating substance beyond the first molecular layer are in a state so close to the volume state that they cannot exercise any specific influence on the phenomena of boundary lubrication, and therefore their properties are not important in this respect.

A different point of view has been expressed by the authors of the present paper[2], and by a number of other Soviet scientists[3].

According to their conception, based on a number of experiments carried out mostly by new and original methods, the influence of the solid wall extends through many molecular layers of a liquid containing polar molecules, producing changes in their properties (as compared with those of the bulk phase) that have a considerable effect on the mechanism of lubrication.

The time is now ripe to summarize the experimental data, which show that in the above-mentioned divergence of views preference must be given to the conception of long-distance surface action. A comprehensive survey should include investigations of the most varied effects for different liquids. As such surveys have already been published[4,5], particularly as regards the application of an analogous conception to the theory of the stability of colloids, worked out by the author[6,7] as well as by VERWEY AND OVERBEEK[8], GLAZMAN AND DYKMAN[9] and others, we shall confine ourselves to data directly concerning such behaviour and properties of boundary oil films as are closely related to their lubricating action (oiliness).

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A STUDY OF VISCOSITY IN THIN BOUNDARY FILMS OF LUBRICATING OILS AND OTHER ORGANIC LIQUIDS

One of the methods of establishing the specific properties of boundary films is to measure their viscosity. However, owing to the considerable experimental difficulties involved, the majority of the previous studies either have been erroneous or have not reached clear and comprehensive conclusions. Special attention is deserved by the work of BASTOW AND BOWDEN[10], who, in order to determine the viscosity, studied the radial flow in a narrow slit between parallel planes. They based their conclusion on a comparison of direct (optical) determination of the gap-width between the plane with the value obtained from the measured resistance to flow of the liquid in the slit and the value of its bulk viscosity. The computed width proved to be on an average 0.1-0.2 μ less than that obtained by light interference. As the average error in the determination of the width of the slit was of the same order of magnitude, BASTOW AND BOWDEN concluded that their experiments contradict the measurements that point to changes in the viscosity of the same liquids at a distance of over 0.2 μ from a solid wall.

One could agree with the authors if they had confined themselves to the above conclusion. However, they assumed without sufficient grounds that changes in viscosity also do not take place in thinner liquid layers adjacent to walls. Yet their experiments allow of an opposite interpretation. Despite the arbitrary extrapolation of the results obtained, BOWDEN based his further investigations of boundary lubrication on the denial of the existence of peculiar properties in the wall-adjacent liquid layers at a distance of less than 0.1 μ.

Returning to the same subject in his work on the polymolecular adsorption of vapours on smooth surfaces, BOWDEN tried to confirm his point of view. However, in this paper[11] too, BOWDEN's conclusions constitute an ungrounded extrapolation of the experimental data, which in themselves are not suitable for an estimation of the range of surface action, inasmuch as the investigation of vapour adsorption was carried out only up to the relative pressure of 0.95. It is not surprising, therefore, that the investigations of vapour adsorption in the immediate proximity of the saturation point performed by ZORIN AND DERYAGUIN[12], using an optical method, led to opposite results and conclusions.

We shall now consider the results of direct measurements of viscosity in boundary layers of organic liquids, oils and polymers, performed by a precise and completely original method. These results point indisputably to the fact that in the boundary layers of up to 0.1 μ (and more, in some cases) the viscosity has a value differing from that in the bulk.

MEASUREMENT OF VISCOSITY IN BOUNDARY LAYERS BY THE "BLOW-OFF" METHOD

The shortcoming of all the methods hitherto employed in the investigation of viscosity in thin films lies in the circumstance that these methods, even if we disregard their other defects and sources of error, yield only average effective values of the viscosity in the slit or in a layer of given thickness[13]. Some methods, as for instance those based

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on the flow of a liquid through porous media[14], yield results that are even less definite, since the liquid passes through irregularly shaped pores for which the thickness of the layers is completely indeterminable.

The "blow-off" method devised by the authors[15,16] permits an exact determination of viscosity as a function of the distance from the solid wall, the latter being determined to within $\pm$ 5 Å.

EXPERIMENTAL METHOD

One of the sides of a plane-parallel slit 0.2 mm wide (Fig. 1) was covered with a film of the liquid under investigation over 10 μ thick. A constant stream of air blown through the slit produced a laminar flow in the film, giving it a gently sloping wedge-shaped form. Owing to the fact that the flow of the film was caused solely by the shearing stress of the air stream, which was uniformly distributed over the whole surface of the film, the flow was one-dimensional as well as laminar. In other words, the velocity of the liquid particles depended exclusively on the distance from the solid wall (z) but not on any other coordinates. Thus the flow in the liquid layer was similar to that in a sheared deck of ordinary playing cards. An elementary layer of the liquid, parallel to the slit wall, moved as a whole parallel to the wall with a velocity $u = u(z)$, increasing according to a definite function of the distance to the wall.

This result is caused by the fact that, owing to the absence of volume forces, the state of stress in the film is homogeneous, and therefore the shear stress is the same at all points. If the viscosity were the same at all distances from the solid wall too, then it would follow that the velocity gradient $\partial u/\partial z$ would also be everywhere the same, and u would be proportional to z. In this case the film would assume the shape of the exact wedge bounded on top by an inclined plane; and vice versa, any variation in the value of the viscosity on approaching the wall would bring about a deviation from the strictly wedge-shaped form of the film.

Thus we can judge the variations of viscosity near the solid wall from the profile of the film obtained after blowing-off. In fact, the resulting film profile represents on a definite scale the velocity profile of the liquid near the solid wall.

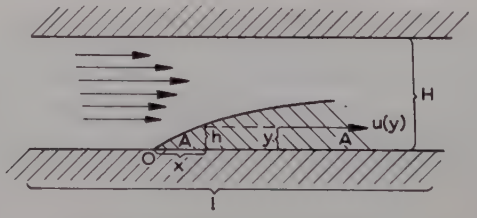

Fig. 1. Scheme of blow-off method.

As proof of this, it is sufficient to point out that if we place the origin of the coordinates (O) on the wetting perimeter (Fig. 1) with the axis OX directed along the wall, and the axis OZ perpendicular to it, then the abscissa x of a point of the film profile, situated at a distance h from the wall, expresses the distance travelled by the corre-

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sponding elementary layer of the liquid during the blowing-off time τ. But the distance travelled is proportional to the velocity: $x = u\tau$; from which follows that the profile of the film represents the velocity profile in the liquid layers near the solid wall.

Applying Newton's law of viscosity, we find the following formula for the viscosity of the liquid at a distance h from the wall:

$$\eta = T\tau \frac{dh}{dx}. \tag{1}$$

The right-hand part of the formula contains the steepness dh/dx of the film profile at the spot where the thickness is equal to h. T denotes the shear stress in the layer of liquid, caused by the air flow. By determining the film profile obtained after blowing-off, we can establish the law of variation of viscosity as a function of the distance from the solid wall. Thus our main problem is to determine exactly the profile of a very thin film in the interval of thickness in which the variation in viscosity takes place under the influence of the solid wall.

Depending on the nature of the liquid and the solid wall, the corresponding layer thickness may vary greatly in order of magnitude. In polymer liquids and solutions, variations of viscosity may extend to distances up to 7-8 μ from the wall. For monomer substances and common oils the layer is much thinner: about 10^{-5} cm. Hence, the optical methods chosen to measure the thickness and profile of the film will vary greatly depending on the object under investigation. In the first case a fairly accurate estimate of the velocity profile and the distribution of viscosity near the wall may be obtained by photographing the interference fringes of equal thickness, obtained by viewing the film in monochromatic light[17] (see below).

A far more sensitive and precise method is necessary in measuring the film thickness in common liquids and oils. We chose a method based on the determination of the parameters of the elliptical polarization of the light reflected from various regions of the film. The necessity for determining the thickness in various regions of a film of unequal thickness made it impossible to apply the usual polarization goniometers and methods of observation requiring wide beams. The narrowing of the incident beam leads to a lowering in the intensity of the reflected light, which made the accurate determination of its state of polarization impossible.

This difficult problem has been successfully solved by means of a special modulation method of analysis of the reflected polarized light, using a photoelectronic multiplier and an oscillograph. As a detailed description can be found in the original paper[16], we shall confine ourselves to describing the scheme of the set-up (Fig. 2) and the method of measurement.

The slit (A), illuminated by a Hg lamp, under 120 V a.c. with a light filter (F_2) isolating the line λ = 5769-5790 Å, was projected into the film under investigation, by means of an object-lens (L); a, aperture diaphragm; P_1, iodine-quinine polaroid, on the measuring limb; P_2, polaroid set in rotation around the reflected beam as an axis with a frequency of about 1 rev/sec. The modulated light fell on the photoelectronic multiplier, the voltage on which was increased by an amplifier with an RC

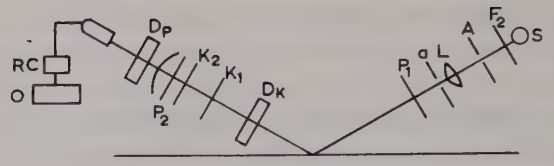

Fig. 2. Optical arrangement for determining velocity profile.

filter and transmitted to the cathode oscillograph O serving as an indicator of the presence or absence of the modulation in the photocurrent.

K_1 and K_2 are two quarter-wave plates; the principal axes of K_1 are directed at an angle of 45° to the plane of incidence, the plate K_2 can be rotated and is on the measuring limb. D_K an D_P are two thick calcite plates cut not quite parallel to the optical axis; D_P serves to depolarize the beam in order to eliminate the influence of the sensitivity of the photocathode to the direction of polarization; D_K, the "decoherenter", serves to eliminate the coherence of $\parallel$ and $\perp$ components of the beam.

With the decoherenter D_K in the "in" position to prevent modulation, it is necessary and sufficient to rotate the polarizer P_1 to such a position that the $\parallel$ and $\perp$ components of the reflected beam become equal. With the decoherenter in the "out" position to prevent a renewed modulation of the photocurrent it is necessary and sufficient to orient the optical axes or the plate K_2, which serves as an analyzer, so that they make an angle of 45° with the plane of polarization of the light transmitted by plate K_1. Calculations are made in the usual manner with the azimuths obtained[16].

The technique of measuring was as follows.

When the film on the surface of the steel plate had been blown off by an air current during time τ, the apparatus was demounted, the plate with the film was set on a micrometer slide, and by moving the latter the film thickness in various regions was measured. After that, a graph was plotted representing the film profile.

As the films of some liquids and solution were not very stable and evinced a tendency to disintegrate into drops, a different procedure was applied in this case. The thickness was measured not after but during blowing-off at a definite distance x_0 from the wetting line. For that purpose the chamber lid was made transparent. For rapid optical measurements the following modification of the technique was particularly convenient. The oil film was smeared on the underside of a glass prism that served as a lid for the blowing-off chamber, the angle of incidence of the polarized light being 45°; complete internal reflection was thus observed; the amplitudes of the component oscillations parallel and normal to the plane of incidence remained constant, but a phase shift appeared. In the presence of the film this shift varied, depending on the thickness of the film.

The advantage of the above-mentioned technique lies in the fact that only one azimuth needs to be measured, instead of two.

By plotting the thickness of the film h against the value $U = x_0/\tau$ the results of the measurement made according to the second variant were brought to a form representing

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the film velocity profile in the proximity of the solid wall, as was done in the first variant (τ is the period of time from the beginning of blowing-off to the moment of measuring; h is the thickness measured at that moment). Obviously the abscissa expresses the velocity of the layers at a distance h from the wall. Thus the graph gives the velocity profile. Its x_0 was difficult to determine; we usually plotted $1/\tau$ on the axis of the abscissa, which resulted in the same velocity profile but on an arbitrary scale.

Figs. 3, 4, 5, 6 and 7 show the results obtained by V. V. KARASSEV; Figs. 3 and 5 were obtained by the first method, the rest by the second.

RESULTS OF THE MEASUREMENTS

Fig. 3 refers to non-polar vaseline oil; the polar impurities were removed by a special procedure worked out by Professor ELOVICH, involving the use of a platinum catalyst at high temperature.

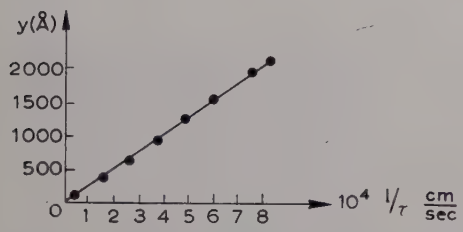

Fig. 3. Velocity profile for specially purified vaseline oil on a steel surface, obtained by analysis of film profile after blowing; $t = 20°C$.

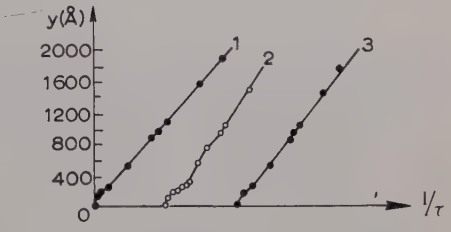

Fig. 4. Velocity profiles of 0.01% solutions of chlorine derivatives of tetracosane in vaseline oil, on a steel surface, obtained in the process of blowing.
(1) Monochlorotetracosane solution, $t = 23°C$;
(2) Trichlorotetracosane solution, $t = 18.6°C$;
(3) Hexachlorotetracosane solution, $t = 25°C$.

We see that the viscosity of non-polar vaseline oil remains a constant value equal to its value in the bulk up to a distance of about 10^{-7} cm from the wall. Similar results have been obtained dozens of times, which proves them to be correct beyond any reasonable doubt. Nevertheless, the addition of fatty acids or ethers in minute concentrations can disturb the linearity of the velocity profiles. With an increase in concentration the film profile becomes irregular and jagged, while a still greater increase of the concentration makes the film unstable: it no longer wets the surface, which is covered with an adsorbed film of a surface-active substance. Fig. 4 represents the velocity profile when a monochloroparaffin, trichloroparaffin or hexachloroparaffin are added to the vaseline oil in a concentration of 0.01%. In this case the form of the profile changes and assumes a characteristic break of about 0.025 μ in thickness. Similar results are obtained in the case of some polar substances in the pure form (see Fig. 5). In some cases, as for instance for incompletely hydrated benzanthrone (Fig. 6), the profile obtained reveals lower viscosity near the wall, which is presumably connected

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with the ring structure of the molecules. This structure enables the molecules to become orientated horizontally near the wall, and this leads to a lowering of viscosity.

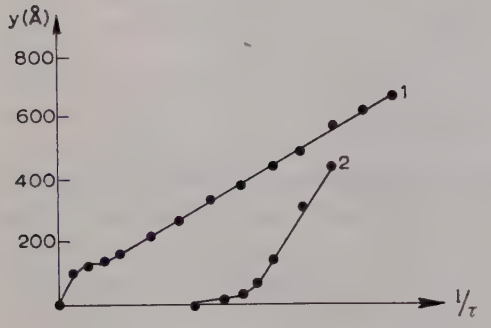

Fig. 5. Velocity profiles of esters on the surface of steel, obtained by analysis of film profiles after blowing. (1) Amyl sebacate; (2) Dibutyl phthalate.

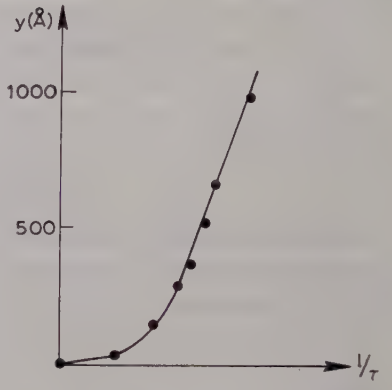

Fig. 6. Velocity profiles of incompletely hydrogenated benzanthrone on a glass surface, obtained during blowing.

DISCUSSION

Inasmuch as viscosity is a structure-sensitive property the results obtained reveal that structural peculiarities occur in the boundary layers of a liquid in which polar molecules are present in the minutest concentration. The fact that the structure is affected by minute concentration of surface-active substances indicates that the action of the latter cannot be due to their presence throughout the film, but is connected with the formation of a definite monolayer. The appearance of sudden changes in the viscosity, and hence also in the structure at distances up to 0.1 μ, proves that the orientated monolayer is in some way able to affect the orientation of adjacent molecules of the non-polar solvent, and that this influence extends throughout hundreds of molecular layers.

This conclusion is particularly supported by the results (Fig. 4) of the experiment with solutions of chloroparaffins in vaseline oil. The jagged curves representing the velocity profile point to the fact that the structure of the boundary layers of liquids can change abruptly at a certain distance from the solid wall; this confirms the conclusion made previously in the case of measurement of the adsorption of vapours of volatile liquids near the saturation point.

The results obtained for fatty acid and ether (Fig. 7) solutions in vaseline oil are rather complicated and deserve special consideration. In the case of weak concentration of surface-active molecules the velocity profile assumes a rather irregular shape, which evidently points to the structural heterogeneity of the corresponding layers of the solvent. This heterogeneity can be explained by the circumstance that different struc-

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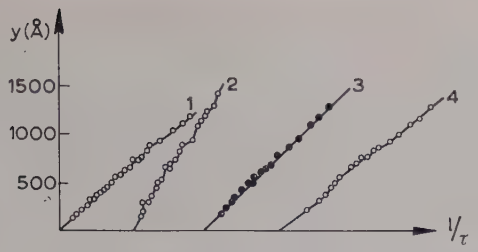

Fig. 7. Velocity profiles of solutions of stearic acid and amyl sebacate on a glass surface during blowing.
(1) 0.000021 % stearic acid; $t = 18°C$. (3) 0.0025 % amyl sebacate; $t = 18°C$.
(2) 0.00054 % stearic acid; $t = 14°C$. (4) 0.0060 % amyl sebacate; $t = 18°C$.

tures of the wall-adjacent layer of the solution are possible, depending on the orientation of the adsorbed molecules, which in turn may vary over the surface.

In a number of cases, if the layer is left undisturbed, we failed to observe any further appearance of irregularities in the profile, and in fact the existing ones were smoothed out. It follows that the film profile obtained after blowing-off assumes its jagged shape as a result of deformation during laminar flow and not because of its thermodynamic instability. The effect is similar to that of the formation of slip bands in plastic deformation[18] and points also to the heterogeneous structure of the boundary layer. At the same time the fluidity preserved by the boundary layer even under the small shear stress caused by the air stream shows that the mechanical properties of a liquid layer differ greatly from those of a plastic solid body, although there are apparently some exceptions to this rule; moreover, the resistance of the boundary layer to thinning points to the difference between its properties and those of the bulk liquid.

It may be supposed that the boundary lubrication layer is in a state similar to that of liquid crystals with a structure in which the main part is played by the orientation of rod-shaped molecules.

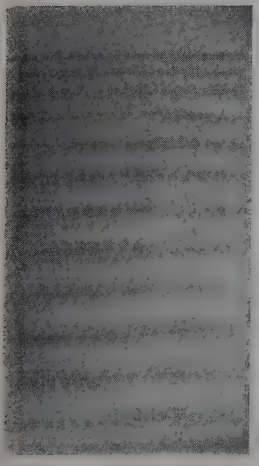

Fig. 8. Photograph of the interference pattern formed on a steel surface when blowing-off a polymer of vinyl butyl ether. $M = 600$; $\tau = 48$ min; $\triangle P = 20$ mm Hg; $t = 20°C$; $C = 100$ % (M is molecular weight, τ is blowing-off time, $\triangle P$ is pressure drop, t is temperature, C is concentration). The direction of the air jet: ↓.

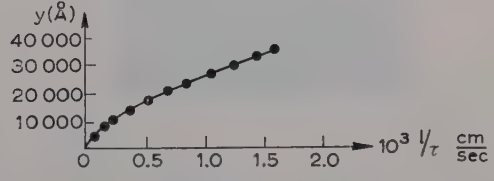

Fig. 9. Velocity profile on steel surface for vinyl butyl ether polymer. $M = 600$; $\tau = 48$ min; $\triangle P = 20$ mm Hg; $t = 20°C$; $C = 100\%$.

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The chief difference from liquid crystals is that in the latter the solid wall causes an orientation spreading at an indefinite distance, while with liquids the distance is quite definite and small.

The intermediate case may include some liquids and solutions containing polymers. As we have already shown, in this case, one can get an idea of the viscosity distribution in the proximity of the solid wall from the position of the interference fringes of equal thickness. Fig. 8 is a photograph of poly (vinyl butyl ether) with a molecular weight 600, which was kindly supplied by Professor M. F. SHESTAKOVSKY. The greater density of the fringes in the thin part of the layer points to an increase of the viscosity there. An analysis of the photograph yields the velocity profile of the film on the solid wall, represented graphically in Fig. 9.

The complex phenomena of viscosity changes and the appearance of zones of unstable thickness are observed upon the addition of various vinyl polymers to mineral oils. Since they are described in detail in original papers[17] we shall confine ourselves to showing photographs (Figs. 10 and 11) representing two typical cases.

Fig. 10. Photograph of interference pattern formed on a steel surface when blowing-off a polymer solution of vinyl butyl ether in turbine oil.
$M = 2{,}100$; $\tau = 12$ min; $\triangle P = 20$ mm Hg; $t = 20°C$; $C = 0.04\%$.

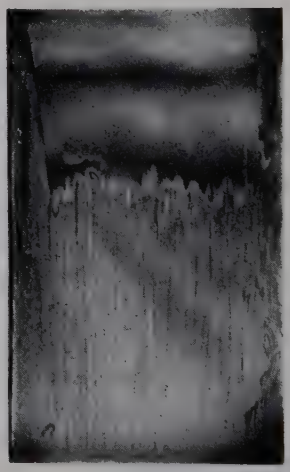

Fig. 11. Photograph of interference pattern formed on a steel surface when blowing-off a polymer solution of vinyl butyl ether in turbine oil.
$M = 3{,}850$; $\tau = 3$ min; $\triangle P = 70$ mm Hg; $t = 20°C$; $C = 0.05\%$.

THE NATURE OF STATIC FRICTION IN BOUNDARY LUBRICATION

THE TWO-TERM LAW OF FRICTION

The results obtained indicate the peculiarities in the structure and fluidity of the boundary layers of lubricating liquids and hence lead us to conclude that these pecu-

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liarities must be taken into consideration in interpreting the phenomena of boundary lubrication and in working out their theory. Owing to lack of space we shall not dwell on these questions, especially since the results of the investigations – in particular those concerning static and kinetic disjoining pressure in thin liquid films[19], the kinetics of the thinning of boundary layers between two solid bodies in contact with one another[20], the interrelation of kinetic friction and molecular orientation[21], etc. – are discussed in a number of other papers. We shall limit ourselves to a consideration of the following important problem.

If the boundary lubrication layer does not possess a yield value, as is indicated by the results of application of the blowing-off method, then how can one explain static friction between solid surfaces, separated by a polymolecular layer? Yet, the existence of static friction in such cases has been convincingly proven in a number of experimental studies[22]. We believe that the correct answer to the question can be found only in the two-term friction law previously formulated by us[23] and experimentally proved[24]. The validity of this law for the interpretation of the mechanical properties of liquid and solid lubricating films has been proved in the work of DERYAGUIN AND LAZAREV[25].

According to the two-term law of friction, the force of static friction F equals:

$$F = \mu (N + S p_0) = \mu N + S\Theta$$
$$(\Theta = \mu p_0),$$

where μ is the "true" coefficient of friction, N the load, S the area of real or molecular contact, and p_0 the adhesion force per unit area of real or molecular contact. This formula, which in form but not in physical content is to some extent analogous to the two-term Coulomb Law (deduced empirically), expresses the idea of the double origin of the force of friction. One part of this force is caused by external pressure N, the other part by the molecular interaction of the surfaces. The law also reflects the divergence between the views of the present authors and BOWDEN, who interprets the friction phenomena[1] by means of the second term of the formula alone, which amounts to the assumption that the "true" coefficient of friction μ equals zero.

Thus, according to BOWDEN and his school, friction depends on the load N only insofar as the latter increases the area S of true or molecular contact between the bodies. This point of view, first formulated by TERZAGHI[26], is in contradiction with experiments in which the force of friction increases with the load in strict accordance with the linear law, despite the fact that either the area of molecular contact cannot undergo essential changes[25] or that this increase in the area is slower than that of the load[27].

To this end we investigated the friction of a plane paraffin block on glass. In order to obtain a large area of contact that was not changed throughout the experiment, the paraffin was preliminarily melted while in contact with the glass surface and then allowed to solidify. In order to be certain that sliding took place not between the layers of paraffin, but on the paraffin-glass interface, the latter was covered with a multi-

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molecular layer of the acid barium or calcium salt of stearic acid, according to the method of BLODGETT AND LANGMUIR. The number of layers n varied from 1-61. Figs. 12 and 13 represent the observed dependence of the force of friction on the load. This dependence bears out the correctness of our two-term law of friction.

The circumstance that the angle of inclination of the straight lines, which is equal to the true coefficient of friction, is independent of the number of molecular layers n proves that the macroscopical asperities of the glass surface have very little influence on the coefficient of friction.

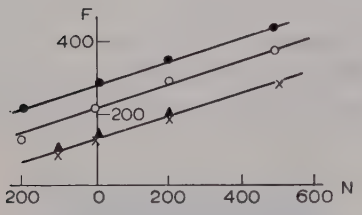

Fig. 12. Friction force plotted against load for paraffin on glass. Lubricant: multimolecular Blodgett-Langmuir layers of acid calcium soap with n molecular layers.
●, $n = 1$; o, $n = 3$; ×, $n = 31$; ▲, $n = 61$.

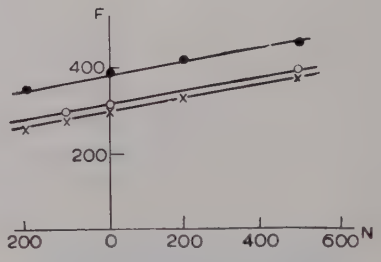

Fig. 13. Friction force plotted against load for paraffin on glass. Lubricant: multimolecular Blodgett-Langmuir layers of barium soap with n molecular layers.
●, $n = 3$; o, $n = 7$; ×, $n = 21$.

The second term in the linear law, according to the above data, declines somewhat as the number of layers n increases from 7 to 9, and remains constant with further increase of n. This decrease in the value of the second term with increasing thickness of the lubricating layer can be easily explained, according to P. A. REHBINDER, by assuming that in thicker lubricating layers the molecular attraction between the glass and the paraffin ceases to have effect, while the adhesive force N depends only on the interaction between the molecules of the lubricant and the paraffin.

Another method of refuting the one-term law and proving the two-term law of friction consists in studying the influence on friction of a variation in the deformability of the areas of contact, with the nature of the surfaces and the conditions of measurement remaining the same.

This idea was tested by U. TOPOROFF in our laboratory. He compared the friction between a metal surface and a glass point with radius of curvature of about 1/10 mm in one case, and between a metal surface and a thin-walled glass ball with radius of curvature equal to several centimeters. The coefficient of friction on the unlubricated metal was always greater in the second case than in the first. But when the metal surface was covered by an adsorbed monolayer of stearic acid this difference disappeared. This experiment furnishes proof of the correctness of the two-term law of friction.

In the case of a thick layer of boundary lubricant, we have the reverse case, when the second term is equal to zero. In fact, in the case of boundary lubrication the second

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term, if referred to unit area, should express the yield value Θ, which in a certain number of cases of boundary lubrication equals zero, as is demonstrated by the results obtained by the blowing-off method. According to current views[28] in that case, static friction should be exactly zero. From our point of view, however, we must take into consideration the first term, which not only explains the presence of static friction, but also provides a basis, in accordance with the experiments, for the one-term friction law of AMONTON, which is strictly valid in cases of boundary lubrication.

The above considerations are, of course, something more than a formal deduction from the observed phenomena. The conclusion drawn, though empiric in origin, contains an essentially new assumption that deserves further investigation and proof: *viz.* that resistance to shear in a thin boundary lubricating film is brought about by a normal load on the film, and appears and disappears with the load. Lack of space does not allow us to present further evidence of this important principle, which, in our opinion, furnishes the only explanation of the mechanism of boundary lubrication consistent with all the experimental data.

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Received for review August, 1957
Accepted November 25, 1957

VOL. 1 NO. 3 DECEMBER 1957

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Office of the Editor:

P.O.Box 71, Delft, The Netherlands.

PUBLICATION

WEAR will have six issues to the volume, approx. 500 pages per volume.
Subscription price: £ 5.7.6. or $ 15.00 or Dfl. 57.— per volume.

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ELSEVIER PUBLISHING CO., AMSTERDAM
Printed in The Netherlands by
NEDERLANDSE BOEKDRUK INRICHTING N.V., 'S-HERTOGENBOSCH